An estimated Canadian DSGE model with nominal and real rigidities

Ali Dib *Department of Monetary and Financial Analysis, Bank of Canada*

Abstract. We develop a dynamic, stochastic, general-equilibrium (DSGE) model due to Ireland (1997) and others and estimate it for the Canadian economy to analyse the real effects of monetary policy shocks. To generate high and persistent real effects, the model combines nominal frictions in the form of costly price adjustment with real rigidities modelled as convex costs of adjusting capital and/or employment. The structural parameters identifying transmission channels are estimated econometrically using a maximum-likelihood procedure with a Kalman filter. The estimated nominal and real rigidities impart substantial and persistent real effects following a monetary policy shock. Furthermore, the results suggest that the monetary authority has accommodated technology shocks and has successfully offset the real effects of money-demand shocks, by actively responding to these shocks. JEL classification: E31, E32, E52

Un modèle d'équilibre général dynamique et stochastique doté de rigidités nominales et réelles et calibré avec des données canadiennes. Dans la présente étude, nous développons un modèle d'équilibre général dynamique et stochastique (EGDS), élaboré par Ireland (1997) et d'autres, et estimons ce modèle pour l'économie canadienne. Afin de générer des effets réels considérables et persistants des chocs monétaires, nous intégrons à ce modèle des frictions nominales et réelles sous la forme de coûts d'ajustement des prix, du capital et de l'emploi. En utilisant la méthode du maximum de vraisemblance et le filtre de Kalman, nous estimons les paramètres structurels du modèle avec des données canadiennes. Les versions du modèle d'EGDS doté de rigidités nominales et réelles génèrent des effets réels significatifs et persistants en réaction à des chocs de politique monétaire. De plus, les résultats suggèrent que l'autorité monétaire réussit bien à contenir les chocs technologiques et à annuler les effets des chocs de la demande de monnaie.

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1. Introduction

In recent years, there has been a renewed interest in the development of macroeconomic models that emphasize the role of nominal price rigidities (see the synthesis by Goodfriend and King 1997 and the references therein). These models rest on the optimizing behaviour of rational agents in a dynamic, stochastic, general-equilibrium (DSGE) environment. However, Chari, Kehoe, and McGrattan (CKM) (2000) point out that these models, despite the merit of explicitly accounting for the relationship between the behaviour of aggregate quantities and prices, and the decisions of utility-maximizing households and profit-maximizing firms, suffer from a serious anomaly: they generate only weak persistence of real and nominal variables in response to money supply shocks.[1] This finding is in contrast to the bulk of evidence indicating that the effects of monetary policy shocks on those variables last several quarters. (see, e.g., Sims 1992; Leeper, Sims, and Zha 1996; Christiano, Eichenbaum, and Evans 2001).

This failure of sticky-price models has sparked a rapidly growing literature aimed at identifying alternative transmission channels of monetary policy shocks. Examples include Kiley (2002), who shows that greater persistence arises only if the degree of increasing returns to scale at the individual firm level is large; Gust (1997), who demonstrates that constraining factor mobility across sectors may increase persistence in the presence of staggered price contracts; Huang and Liu (2002), who find that more persistence can be produced under staggered wage contracts than under staggered price contracts; and Bergin and Feenstra (2000), who obtain more persistence if the share in the fixed factor is sufficiently large in a model that features a staggered price mechanism, non-constant elasticity of substitution production, and factor specificity.

In a static framework of price-setting agents, Ball and Romer (1990) have demonstrated that the degree of nominal rigidity arising from a given menu cost increases with the degree of real rigidity, thus producing larger non-neutralities.[2] Nevertheless, real rigidity does not imply nominal rigidity. In other words, without nominal frictions, prices fully adjust in response to money supply shocks regardless of the extent of real rigidity. Thus, money is neutral in the short term.

Real rigidities may arise in the goods, capital, and/or labour markets. In the absence of real rigidities, the marginal production cost quickly adjusts in response to money supply shocks, implying non-persistent real effects.[3] The incorporation of capital- and labour-market frictions in a model with costly price adjustments induces a gradual response of real variables to aggregate disturbances. In turn, the marginal production costs of price-setting firms also

1 More specifically, CKM (2000) develop a one-shock model with imperfect competition in the goods markets and staggered price contracts, in the spirit of Taylor (1980).

2 The degree of nominal rigidity can be defined as the significance and the duration of nominal shock effects on real variables.

3 In standard sticky-price models with flexible capital and labour inputs, the marginal production cost of price-setting firms is a weighted average of the real rental rate on capital and the real wages.

adjust more slowly. Thus, the combination of nominal and real rigidities can potentially impart a larger nominal price rigidity and a more persistent effect from money supply shocks.

Amano and Wirjanto (1997) use a linear-quadratic model to examine whether there is significant evidence of the effect of adjustment costs on Canadian labour demand. They estimate the relative employment adjustment costs as well as its rate of adjustment towards long-run equilibrium. Their empirical estimates imply that adjustment costs are very significant and are an important feature of Canadian labour demand. On the other hand, Hendry and Zhang (2001) introduce nominal wage and price rigidities, as well as portfolio adjustment costs and monopolistically competitive firms, in a standard limited-participation model. They calibrate their model for the Canadian economy in order to examine how each of these transmission mechanisms affects the size and the length of liquidity effect following a central bank policy action.[4]

Ireland (1997) develops a quantitative dynamic-optimizing model with sticky prices. He estimates the developed model for the U.S. economy using a maximum-likelihood procedure with a Kalman filter. The estimation results leads to a very small degree of nominal rigidity, since the estimate of price-adjusment cost parameter is too small. Furthermore, this sticky price model fails to generate larger persistence of real variables in response to monetary shocks. On the other hand, Dib and Phaneuf (2001) argue that Ball and Romer's (1990) original intuition of combining nominal and real rigidities has the potential to substantially increase the real persistence of monetary effects in DSGE models with sticky prices. They estimate an optimization-based standard sticky-price model and one that combines nominal and real rigidities in the form of price- and emplyment-adjustment costs for the U.S. economy. Nominal friction and real rigidity are modelled as the quadratic costs of changing prices, as in Rotemberg (1982), and as the convex costs of adjusting employment. Their main finding is that, as in Ireland (1997), the estimated standard sticky-price model generates no endogenous real persistence. In contrast, the impact of nominal rigidity substantially increases in the presence of real rigidity, and the model combining both rigidities produces larger and persistent effects of real variables in response to money supply shocks.

In this paper we extend Ireland's (1997) work by combining nominal and real rigidities in a DSGE model and estimate this model for the Canadian economy.[5]

4 Amano and Wirjanto (1997) and Hendry and Zhang (2001) use a closed economy framework for the Canadian economy.

5 Though Canada is a small open economy, using a closed economy framework is still a usefull exercise to estimate and simulate a DSGE model if we do not address issues that require an open economy framework. Furthermore, Khan and Zhu (2002) have estimated a sticky-information model using closed- and open-economy frameworks for Canada and the United Kingdom. They find that open and closed economies lead to similar estimates for both countries. Similarly, Clarida, Galí, and Gertler (2001) argue that the optimal policy problem for a small open economy is isomorphic to that for a closed economy.

Indeed, in addition to the fact that we use Canadian data to estimate various version of DSGE model, we differ from Dib and Phaneuf (2001) by modelling real rigidity as either the convex costs of adjusting capital and/or employment and by using a new specification of employment adjustment cost similar to that used by Cogley and Nason (1995). The presence of capital and/or employment adjustment costs in the same model allows a comparison of the contribution of each type of real rigidity in generating the persistence of real effects of monetary shocks. With various combinations of nominal and real rigidities, we estimate and simulate the developed DSGE model to analyse the real effects of money supply, money demand, and technology shocks, estimate the relative importance of these shocks in driving mouvements in output and inflation, and describe how the Canadian central bank has responded to these shocks.[6]

The structural parameters, including the price- and employment-adjustment cost parameters, are estimated using quarterly, seasonally adjusted Canadian data on output, inflation, and money growth from 1976Q1 to 2000Q4. The parameters are estimated using Hansen and Sargent's (1998) procedure of applying a maximum-likelihood method and a Kalman filter to the model's state-space forms. The combination of nominal and real frictions substantially increases the degree of nominal price rigidity. Because the estimated costs of changing prices rise correspondingly, firms, although they face employment-adjustment costs, are reluctant to change their prices in response to changes in aggregate demand. Furthermore, the estimates of the money-supply-rule parameters indicate that, over the sample period, the central bank has responded to both positive technology and money demand shocks by increasing the money supply.

Performing various simulations based on the estimated models, we find that the models with nominal and real rigidities produce results that differ sharply from those found in standard sticky-price models.[7] The effects of money supply shocks last approximately seven quarters, and money supply shocks contribute substantially to the observed short-run variation in real variables. We also show that arbitrarily increasing the size of price-adjustment costs has no impact on the persistence of real deviations following a money supply shock, unless there are real rigidities. Hence, this result corroborates CKM's (2000) main finding in their sticky-price model.

This paper is organized as follows. In section 2 we present the DSGE model with nominal and real rigidities. In section 3 the calibration and the econometric procedures are described. The estimation results are reported and discussed in section 4. The implications of the estimated models are evaluated in section 5. Section 6 contains concluding remarks.

6 The four estimated versions of the DSGE model are: (i) a standard sticky-price model; (ii) a model with price and capital rigidities, (iii) a model with price and employment rigidities; (iv) a model combining the three types of rigidities.

7 With no real rigidities, the estimated costs of changing prices are always quite small. The impulse response of output following a money supply shock dies after one quarter, and the fraction of the total variance of output attributable to money supply shocks is very small even at short horizons.

2. The model

The basic structure of the model and much of the notation are taken from Ireland (1997), which, in turn, is inspired by Rotemberg (1982), Blanchard and Kiyotaki (1987), Hairault and Portier (1993), and Kim (2000).[8] It is assumed that the economy is populated by a representative household, a representative final-goods-producing firm, a continuum of intermediate-goods-producing firms, and a monetary authority. The representative final-goods-producing firm produces a finished output that it sells on a perfectly competitive market. Nevertheless, each intermediate-goods-producing firm produces a distinct, perishable, intermediate good that it sells on a monopolistically competitive market. Furthermore, each intermediate-goods-producing firm pays two distinct finite costs when it adjusts its nominal price and its labour input.

2.1. Household

The representative household derives utility from consumption, c_t, real money balances, M_t/p_t, and leisure, $(1-h_t)$ where h_t represents total hours worked. The household's preferences are described by the expected utility function,

$$U_0 = E_0 \sum_{t=0}^{\infty} \beta^t u\left(c_t, \frac{M_t}{p_t}, h_t \right), \tag{1}$$

where $\beta \in (0,\ 1)$ is the discount factor. It is assumed that the single-period utility function is specified as

$$u(\cdot) = \frac{\gamma}{\gamma - 1} \log\left[c_t^{\frac{\gamma-1}{\gamma}} + b_t^{\frac{1}{\gamma}} \left(\frac{M_t}{p_t} \right)^{\frac{\gamma-1}{\gamma}} \right] + \eta \log(1 - h_t), \tag{2}$$

where γ and η are positive structural parameters. As in Kim (2000), the preference shock, b_t, can be interpreted as a shock to money demand. This shock follows the autoregressive process:

$$\log\ (b_t) = (1 - \rho_b) \log\ (b) + \rho_b\ \log\ (b_{t-1}) + \varepsilon_{bt}, \tag{3}$$

where $\rho_b \in (-1,\ 1)$ is an autoregression coefficient, and ε_{bt} is a serially uncorrelated shock that is normally distributed with mean zero and standard deviation σ_b.

The representative household enters period t with units of capital, k_t, and nominal money balances, M_{t-1}. During period t, the household supplies capital and labour to each intermediate-goods-producing firm and receives total factor payments, $R_t k_t + W_t h_t$; R_t is the nominal rental rate for capital;

8 The first version of Kim (2000) circulated under the title 'Monetary policy in a stochastic equilibrium model with real and nominal rigidities,' manuscript (New Haven, CT: Yale University, Department of Economics, 1995).

W_t is the nominal wage rate; and h_t and k_t must satisfy $h_t = \int_0^1 h_{jt}dj$ and $k_t = \int_0^1 k_{jt}dj$ for all $t \geq 0$. It also receives a lump-sum nominal transfer, T_t, from the monetary authority and dividend payments from the intermediate-goods-producing firms, $D_t = \int_0^1 D_{jt}dj$. The household uses some of its funds to purchase the final output at the nominal price, p_t, which it then divides between consumption and investment. Investment, i_t, increases the capital stock over time according to

$$k_{t+1} = (1 - \delta)k_t + i_t, \tag{4}$$

where $\delta \in (0, 1)$ is a constant capital depreciation rate. Furthermore, it is assumed that it is costly to intertemporally adjust capital and that the capital-adjustment cost is specified as

$$\mathrm{CAC}_t = \frac{\phi_K}{2}\frac{i_t^2}{k_t}, \tag{5}$$

where $\phi_K > 0$ is the capital-adjustment cost parameter. With this configuration, the cost of changing the capital stock increases with the speed of desired adjustment, giving the household an incentive to change investment gradually.

The household's budget constraint is therefore given by

$$p_t(c_t + i_t + \mathrm{CAC}_t) \leq R_t k_t + W_t h_t + M_{t-1} - M_t + T_t + D_t. \tag{6}$$

Given initial values, the household chooses $\{c_t, M_t, h_t, k_{t+1}\}$, for all $t \geq 0$, to maximize the expectation of the discounted sum of its utility flows subject to the capital accumulation and the budget constraint, with which the Lagrangian multiplier, λ_t, is associated. The first-order conditions of this optimization problem are given in appendix A.

2.2. *The final-goods-producing firm*

The final good, y_t, is produced from a continuum of intermediate goods y_{jt}. Assuming that all intermediate goods are imperfect substitutes with a constant elasticity of substitution θ, the corresponding aggregator function can be defined as

$$y_t \leq \left(\int_0^1 y_{jt}^{\frac{\theta-1}{\theta}} dj\right)^{\frac{\theta}{\theta-1}}, \qquad \theta > 1. \tag{7}$$

Given the relative price vector, the final-goods-producing firm chooses the quantity of intermediate good y_{jt} that maximizes its profits. The optimization problem is

$$\max_{y_{jt}} \left[p_t \left(\int_0^1 y_{jt}^{\frac{\theta-1}{\theta}} dj\right)^{\frac{\theta}{\theta-1}} - \int_o^1 p_{jt} y_{jt} dj\right].$$

The first-order condition implies the following demand function for firm j:

$$y_{jt} = \left(\frac{p_{jt}}{p_t}\right)^{-\theta} y_t, \tag{8}$$

which expresses the demand for good j as a function of its relative price and final output. The final-good price index satisfies

$$p_t = \left(\int_o^1 {p_{jt}}^{1-\theta} dj\right)^{\frac{1}{1-\theta}}. \tag{9}$$

2.3. The intermediate-goods-producing firm

Intermediate-goods-producing firm j hires k_{jt} units of capital and h_{jt} units of labour to produce output, y_{jt}, according to the following constant-returns-to-scale technology:

$$y_{jt} \leq A_t k_{jt}^{\alpha} \left(g^t h_{jt}\right)^{1-\alpha}, \qquad \alpha \in (0,1) \text{ and } g \geq 1, \tag{10}$$

where g is the growth rate of labour productivity (which is also the growth rate of the economy), and A_t is a technology shock that is common to all intermediate-goods-producing firms. The technology shock, A_t, is assumed to follow the autoregressive process

$$\log A_t = (1-\rho_A)\ \log\,(A) + \rho_A\ \log\,(A_{t-1}) + \varepsilon_{At}, \tag{11}$$

where $\rho_A \in (-1,\ 1)$ is an autoregression coefficient and ε_{At} is a serially uncorrelated shock that is normally distributed with zero mean and standard deviation σ_A.

It is well known that money is super neutral in a monopolistic competition framework unless some sort of nominal friction is added to the model (e.g., Rotemberg 1982). Here, nominal rigidity is introduced by the presence of price-adjustment costs. It is assumed that the intermediate-goods-producing firm faces a quadratic cost of adjusting its nominal price given by the following function:

$$\text{PAC}_{jt} = \frac{\phi_p}{2}\left(\frac{p_{jt}}{p_{jt-1}} - 1\right)^2 y_t, \tag{12}$$

where $\phi_p \geq 0$ is the price-adjustment cost parameter. These real costs are measured in terms of the final good. Rotemberg (1982) interprets this quadratic adjustment cost specification as capturing the negative effects of price changes on consumer-firm relationships, which increase in magnitude with the size of the price change and with the overall scale of economic activity, as summarized by total output of the finished good. The price markup is constant under complete price flexibility ($\phi_p = 0$), but it is endogenous when prices are rigid.[9]

The second real rigidity is a labour-market friction. Specifically, intermediate firm j pays convex costs of varying its labour input according to the following adjustment cost function:

$$\text{EAC}_{jt} = \frac{\phi_h}{2}\left(\frac{h_{jt}}{h_{jt-1}} - 1\right)^2 y_t, \tag{13}$$

where $\phi_h \geq 0$ is the employment-adjustment cost parameter. These costs are also measured in terms of the final good, and they directly affect labour demand. The cost of adjusting employment in response to aggregate shocks increases with the speed of the desired adjustment. This gives firms an incentive to undertake employment changes gradually and intertemporally smooth their labour demand. The specification form in (13), which assumes that the marginal cost of adjusting employment is a linear function of its rate of change, is also used by Cogley and Nason (1995) to study the output dynamic propagation in a model with finite capital- and employment-adjustment costs.

With price- and/or employment-adjustment costs, the intermediate firm's optimization problem is dynamic; the intermediate firm j chooses contingency plans for h_{jt}, k_{jt}, y_{jt}, and p_{jt} for all $t \geq 0$ that maximize its expectation of the discounted sum of its profit flows conditional on the information available at time zero:

$$\max_{\{k_{jt}, h_{jt}, p_{jt}\}} E_0 \sum_{t=0}^{\infty} \beta^t \lambda_t \left[D_{jt}/p_t\right], \tag{14}$$

where the instantaneous profit function is given by

$$D_{jt} = p_{jt} y_{jt} - R_t k_{jt} - W_t h_{jt} - p_t \text{PAC}_{jt} - p_t \text{EAC}_{\text{jt}}, \tag{15}$$

subject to constraints (8) and (10), to which the Lagrangian multiplier $\xi_t > 0$ is associated. The firm's discount factor is given by the stochastic process $(\beta^t \lambda_t)$, where λ_t denotes the marginal utility of real income. In equilibrium, this factor represents a pricing kernel for contingent claims. The first-order conditions with respect to k_{jt}, h_{jt}, p_{jt}, and ξ_t are given in appendix B.

With employment-adjustment costs, the price of labour consists of the real wages paid to the household and the marginal cost of adjusting labour in the current and future periods. Let $q_t = \lambda_t / \xi_t$ measure the gross price markup over marginal cost. In the absence of price-adjustment costs ($\phi_p = 0$), the price markup, q_t, is constant and equal to $\theta/(\theta - 1)$. That is, the marginal cost does not change in response to exogenous disturbances.

9 This price-adjustment cost function is similar to those functions used by Hairault and Portier (1993) and Kim (2000).

With nominal price rigidities, the price markup varies in response to exogenous disturbances. For example, following a positive technology shock, the marginal cost curve shifts downward, and since the intermediate-goods-producing firm does not fully adjust its price, both the markup and the output increase. On the other hand, a positive aggregate demand shock shifts the marginal revenue curve upward, and, given that prices are sticky, the markup decreases, while labour demand and output increase. With nominal and real rigidities, labour demand gradually increases following a positive money supply shock, inducing a slower adjustment of real wages. Since the marginal cost depends on real wages, it also changes more slowly.

2.4. *Monetary authority*

Like Ireland (1997), we adopt a money-supply rule. It is also assumed that the monetary authority responds in a systematic fashion to technology and money-demand shocks. Thus, monetary policy may be partially endogenous. The newly created money is transfered to the representative household during each period, so that

$$M_t - M_{t-1} = T_t, \tag{16}$$

where M_t is the per capita money stock.

The gross growth rate of the money stock, $\mu_t = M_t/M_{t-1}$, evolves according to

$$\log(\mu_t) = (1-\rho_\mu)\log(\mu) + \rho_\mu \log(\mu_{t-1}) + \omega_A\varepsilon_{At} + \omega_b\varepsilon_{bt} + \varepsilon_{\mu t}, \tag{17}$$

where $\rho_\mu \in (-1, 1)$ is an autoregression coefficient and $\varepsilon_{\mu t}$ is a white noise shock with zero mean and standard deviation σ_μ. In the event that $\omega_A = \omega_b = 0$, monetary policy becomes purely exogenous.

2.5. *Symmetric equilibrium and resolution*

In a symmetric equilibrium, all intermediate-goods-producing firms are identical. They make the same decisions, so that $k_{jt} = k_t$, $h_{jt} = h_t$, $p_{jt} = p_t$, $y_{jt} = y_t$, and $D_{jt} = D_t$. Let $r_t = R_t/p_t$, $w_t = W_t/p_t$ and $\pi_t = p_t/p_{t-1}$ denote the real capital rental rate, the real wage, and the gross inflation rate, respectively. The symmetric equilibrium is composed of an allocation $\{y_t, c_t, M_t/p_t, h_t, k_t, i_t\}_{t=0}^{\infty}$ and a sequence of prices and co-state variables $\{w_t, r_t, \pi_t, \lambda_t, q_t\}_{t=0}^{\infty}$ that satisfy the household's and the intermediate-goods-producing firm's first-order conditions, the aggregate resource constraint, money market-clearing condition, and the stochastic processes of money supply, money demand and technology shocks.

In the model, h_t, r_t, π_t, q_t, A_t, b_t, and μ_t are stationary variables. However, the remaining variables must be made stationary by defining the following:

$$\tilde{c}_t = \frac{c_t}{g^t}, \tilde{m}_t = \frac{M_t/p_t}{g^t}, \tilde{k}_t = \frac{k_t}{g^t}, \tilde{w}_t = \frac{w_t}{g^t}, \tilde{y}_t = \frac{y_t}{g^t}, \text{ and } \tilde{\lambda}_t = \frac{\lambda_t}{g^{-t}}.$$

Taking these definitions into account and given $\tilde{k}_0$, $\tilde{m}_{-1}$, h_{-1}, and $\{A_t, b_t, \mu_t\}_{t=0}^{\infty}$, one may obtain equilibrium conditions for the allocation $\{\tilde{y}_t, \tilde{c}_t, \tilde{m}_t, h_t, \tilde{k}_t\}_{t=0}^{\infty}$ and the sequence of prices and co-state variables $\{\tilde{w}_t, r_t, \pi_t, \tilde{\lambda}_t, q_t\}_{t=0}^{\infty}$.

For any stationary variable $\tilde{x}_t$, we define $\hat{x}_t = \log(\tilde{x}_t/\tilde{x})$ as the deviation of $\tilde{x}_t$ from its steady-state value. The log-linearized approximation for the model equilibrium system aroud steady-state value is found using the method of Blanchard and Kahn (1980). Thus, the log-linearized version of the model can be written in its state-space form as

$$\hat{\mathbf{s}}_{t+1} = \Phi_1 \hat{\mathbf{s}}_t + \Phi_2 \varepsilon_{t+1}, \tag{18}$$

$$\hat{\mathbf{d}}_t = \Phi_3 \hat{\mathbf{s}}_t, \tag{19}$$

where $\hat{\mathbf{s}}_t = (\hat{k}_t, \hat{m}_{t-1}, \hat{h}_{t-1}, \hat{A}_t, \hat{b}_t, \hat{\mu}_t)'$ is a vector of state variables that includes predetermined and exogenous variables; $\hat{\mathbf{d}}_t = (\hat{\lambda}_t, \hat{q}_t, \hat{m}_t, \hat{h}_t, \hat{y}_t, \hat{w}_t, \hat{r}_t, \hat{c}_t, \hat{\pi}_t)'$ is the vector of control variables; and the vector $\varepsilon_{t+1} = (\varepsilon_{At+1}, \varepsilon_{bt+1}, \varepsilon_{\mu t+1})'$ contains technology, money demand, and money supply shocks. The solution is a restricted vector autoregression (VAR) in the sense that the elements of matrices, Φ_1, Φ_2, and Φ_3, depend on the structural parameters of the model. The state-space solution in (18)–(19) is used to estimate the underlying structural parameters and simulate the model.

3. Calibration and estimation procedures

There are 22 structural parameters in this model, 7 of which will not be estimated, but instead are fixed prior to estimation. This is because the data set omits the relevant series for these parameters, such as capital and investment. Therefore, these parameters are pinned down at values common in the business cycle literature. In particular, the discount factor β is set at 0.992, implying an annual steady-state real interest rate of 4.5%. The parameter η, denoting the weight put on leisure in the representative household's utility function, is set at 1.42. Thus, the representative household spends roughly one-third of its time in market activities. As in Ireland (1997), the parameter b is set equal to 0.535, so that the steady-state consumption velocity of money in the model matches that observed in the Canadian data. We set ϕ_k, the capital-adjustment cost parameter, equal to 1, which produces an average capital-adjustment cost of about 0.3% of quarterly GDP. This value is consistent with the accepted notion that capital-adjustment costs are economically significant but small (see Mendoza 1991).[10] The capital share in production, α, and the depreciation rate, δ, are assigned values of 0.33

10 Based on an estimated DSGE model, Kim (2000) finds that the capital-adjustment costs represent 5% of investment in the U.S. economy.

abd 0.025, respectively.[11] Finally, the parameter that measures monopoly power in intermediate-goods markets, θ, is set equal to 6, implying a gross steady-state price markup of 1.2. This value matches the benchmark one of 1.2 in Rotemberg and Woodford (1995).

The estimates of the price- and employment-adjustment cost parameters are slightly affected by the choice of ϕ_k and θ. The degree of the nominal rigidity increases with ϕ_k; however, the estimated values for ϕ_h decrease when ϕ_k increases. Price adjustment becomes more rapid when θ increases (i.e., when the markets become more competitive), so price-adjustment costs become larger. We also estimate the model with $\phi_k = 3$ and $\theta = 9$, and the estimation results presented below are quite robust to the choice of these parameters.

The non-calibrated parameters are estimated using Hansen and Sargent's (1998) method: a Kalman filter is applied to a model's state-space solution to generate series of innovations, which are then used to evaluate the likelihood for the sample. The state-space solution in (18)–(19) is a restricted first-order VAR driven by three innovations. Therefore, the structural parameters embedded in Φ_1, Φ_2, and Φ_3 can be estimated by a maximum-likelihood procedure using data for three series.[12] Hansen and Sargent (1998) also show that the maximum-likelihood estimator is consistent and asymptotically efficient.

Using a first-order VAR for the detrended output, the inflation rate, and the money growth rate, we estimate this DSGE model using quarterly Canadian data from 1976Q1 to 2000Q4. The output is real per capita GDP, the inflation rate is measured by changes in the implicit GDP deflator, while the money growth rate is measured by the changes in M2 per capita.[13] The series for output and money stock are expressed in per capita terms using the total civilian population aged 15 and over.[14]

4. Estimation results

In this section we discuss the estimation results of the structural parameters for four versions of the model. The first version is a standard sticky-price model (SSP model), where capital and employment are perfectly flexible. It is the model estimated by Ireland (1997) for the U.S. economy. In addition to this model, we also estimate three other versions combining nominal and real

11 Mendoza (1991) uses these values to calibrate the depreciation rate and the share of capital for the Canadian economy.

12 The elements of Φ_1, Φ_2, and Φ_3 are non-linear functions of the model's structural parameters.

13 The use of M2 as a measure of money stock is motivated by the existence of a stable money-demand relationship in Canadian data for M2, but not for the narrower aggregate M1. In fact, M1 has substantially increased since the charter banks were not required to handle reserves in 1992.

14 In the Canadian data, inflation and nominal M2 growth rates are non stationary. Thus, before the model is estimated, these variables are rendered stationary by regressing the logarithm of each one on a constant and a time trend.

TABLE 1
Maximum-likelihood estimates and standard errors: 1976Q1 to 2000Q4

Parameters	SSP model	PCR model	PER model	PCER model
ϕ_p	2.8048	14.356	44.073	26.626
	(2.5097)	(4.4216)	(25.288)	(10.213)
ϕ_h	–	–	1.8538	0.4377
	(–)	(–)	(1.0377)	(0.2955)
γ	0.3005	0.3887	0.3940	0.4366
	(0.1174)	(0.1687)	(0.2537)	(0.2504)
ρ_b	0.9998	0.9999	0.9997	0.9998
	(0.0055)	(0.0053)	(0.0060)	(0.0056)
σ_b	0.0210	0.0200	0.0241	0.0222
	(0.0043)	(0.0034)	(0.0071)	(0.0047)
g	1.0033	1.0034	1.0033	1.0034
	(0.0003)	(0.0004)	(0.0003)	(0.0003)
A	218.04	219.98	217.98	220.67
	(2.8323)	(3.9294)	(5.5045)	(6.4944)
ρ_A	0.9578	0.9592	0.9310	0.9471
	(0.0259)	(0.0298)	(0.0280)	(0.0276)
σ_A	0.0057	0.0064	0.0064	0.0064
	(0.0005)	(0.0006)	(0.0005)	(0.0005)
μ	1.0235	1.0243	1.0238	1.0240
	(0.0015)	(0.0013)	(0.0015)	(0.0015)
ρ_μ	0.7370	0.7039	0.7592	0.7321
	(0.0534)	(0.0485)	(0.0572)	(0.0498)
σ_μ	0.0015	0.0017	0.0013	0.0015
	(0.0003)	(0.0003)	(0.0003)	(0.0003)
ω_A	0.1480	0.1498	0.0616	0.1072
	(0.0438)	(0.0477)	(0.0419)	(0.0431)
ω_b	0.3225	0.3347	0.2854	0.3054
	(0.0610)	(0.0528)	(0.0793)	(0.0608)

rigidities: (1) a model with price and capital rigidities (PCR model), (2) a model with price and employment rigidities (PER model), and (3) a model with price, capital, and employment rigidities (PCER model).[15] Table 1 reports maximum-likelihood estimates and their standard errors for the four models.

Almost all parameter estimates are highly significant at conventional confidence levels, consistent, and economically meaningful. The estimate of the price-adjustment cost parameter, ϕ_p, is significantly larger when both nominal and real rigidities are considered; the estimate of ϕ_p is 2.80 in the SSP model, while it is 14.36 (44.07) in the PCR model (and the PER model), and 26.63 in the PCER model. With $\phi_p = 26.63$, changing nominal prices by 1% involves paying a cost that amounts to about 0.13% of real GDP per quarter. Using post-war U.S. data, Ireland's (1997) estimate of ϕ_p is 4.05 in his standard sticky-price model, while Dib and Phaneuf's (2001) estimate is 4.26 in their SSP model and about 93 in their model combining price- and employment-adjustment costs.

15 In the SSP model, $\phi_k = \phi_h = 0$; in the PCR model, $\phi_h = 0$; and in the PER model, $\phi_k = 0$.

The employment-adjustment cost parameter, ϕ_h, is estimated at 1.85 in the PER model and at 0.44 in the PCER model, but with relatively high standard errors. Hence, the marginal cost of changing employment by 1% amounts to roughly 1.85 (0.44)% of real GDP per quarter in the PER (PCER) model. These estimates are similar to those found in Amano and Wirjanto (1997). Moreover, using Shapiro's (1986) estimates for the U.S. economy to calibrate the employment-adjustment cost parameter, Cogley and Nason (1995) set ϕ_h equal to 0.36 in their model with capital and employment rigidities. This value is close to that estimated in the PCER model.

The estimate of γ, the constant elasticity of substitution between consumption and real balances in utility function, is equal to 0.30 in the SSP model, while it is about 0.40 in the models combining nominal and real rigidities. On the other hand, the estimates of the parameters of money demand shock process indicate that these shocks are highly persistent and largely volatile. Indeed, in all models, the estimated values of ρ_b exceed 0.99, while those of σ_b are about 0.022. These estimates are similar to those estimated by Ireland (1997), Kim (2000), and Dib and Phaneuf (2001) for the U.S. economy.

The estimated value of g, the gross growth rate in this economy, is 1.0033 in all models, while that of A is about 220. Thus, the annual rate of real per capita GDP growth is about 1.40%. Technology shocks appear to be highly persistent and moderately volatile, with ρ_A and σ_A estimated at 0.95 and 0.006, respectively. These estimated values are similar to those normally assumed for the technology process parameters in RBC studies.

The estimate of the money growth rate, μ, is 1.024 in all models. However, the serial correlation in the money growth process, ρ_μ, ranges between 0.70 in the PCR model and 0.76 in the PER model. The estimated value of σ_μ, the variation in money growth under a partially endogenous monetary policy rule, is 0.0015. Thus, this value is too small, compared with that estimated directly in an unrestricted VAR, where the estimate of σ_μ is about 0.0063. The parameter ω_A, which measures the response of the monetary authority to technology shocks, is estimated at 0.15 in the two models where labour is perfectly flexible; however, when it is costly to adjust labour, ω_A is estimated at 0.06 and 0.11 in the PER and PCER models, respectively. The response to technology shocks is procyclical, and it is less important in models with employment-adjustment cost than in those with perfectly flexible labour. On the other hand, the parameter measuring the response of a monetary authority to money demand shocks, ω_b, is estimated at about 0.30 in the four models. With $\omega_b > 0$, the monetary authority's response is countercyclical, and the larger value estimated for ω_b indicates that the monetary authority aggressively responds to money demand shocks to offset their real effects and to smooth the inflation rate.

5. Evaluating the model

This section evaluates the performance of the four models using the estimated and calibrated values for their structural parameters. We first calculate the impulse-response functions of output, real wages, hours, and the inflation rate to money supply, technology, and money demand shocks. The impulse responses are computed for 1% shocks and expressed as the percentage deviation of a variable from its steady-state value. Next, we calculate the forecast-error variance decomposition of detrended output, inflation, and money growth at various horizons.

5.1. Impulse-response functions

Figure 1 shows the impulse responses for a 1% increase in the money growth rate. In the SSP model, where there is only the nominal rigidity, output, real wages, hours, and the inflation rate immediately jump above their steady-state values, but their responses exhibit no significant persistence. However, the combination of nominal and real rigidities imparts a substantial degree of nominal price rigidity. Indeed, in the models that have both nominal and real rigidities, output, real wages, and hours increase by more than 2.8% on impact, and their responses last for more than seven quarters after the shock. Even though the immediate effect of a money supply shock on the inflation rate is positive and highly significant, its response exhibits little persistence; it dies out at the end of the fourth quarter.

The real monetary shock effects are more significant and persistent in the presence of employment rigidity. This merely reflects the slow adjustment of real wages and employment to their steady-state level in response to a money supply shock. Indeed, in the presence of employment-adjustment costs, intermediate-goods-producing firms have to pay a cost for changing the quantity of the labour input. They also have to pay much larger price-adjustment costs. As a consequence, they remain reluctant to change their prices in response to money supply shocks. Nevertheless, the employment-adjustment costs play a significant role because, once the intermediate-goods producers have allowed output to increase in response to a positive shock to aggregate demand, firms are less willing to lower output immediately. Thus, output movements are more persistent. Overall, these results confirm that nominal rigidities combined with real frictions are an important source of the real persistence.

Figure 2 shows how the economy responds to a 1% money supply shock in the SSP model. To test whether more persistence can be obtained if the size of price-adjustment costs is increased, we set ϕ_p equal to 26.63, as estimated in the PCER model, and keep the other structural parameters at their estimated and calibrated values for the SSP model. The nominal rigidity produces a large output effect, but no persistence. Although the contemporaneous responses of the variables are stronger with larger price-adjustment costs, the real money effects do not exhibit more persistence. Hairault and Portier (1993), Ireland

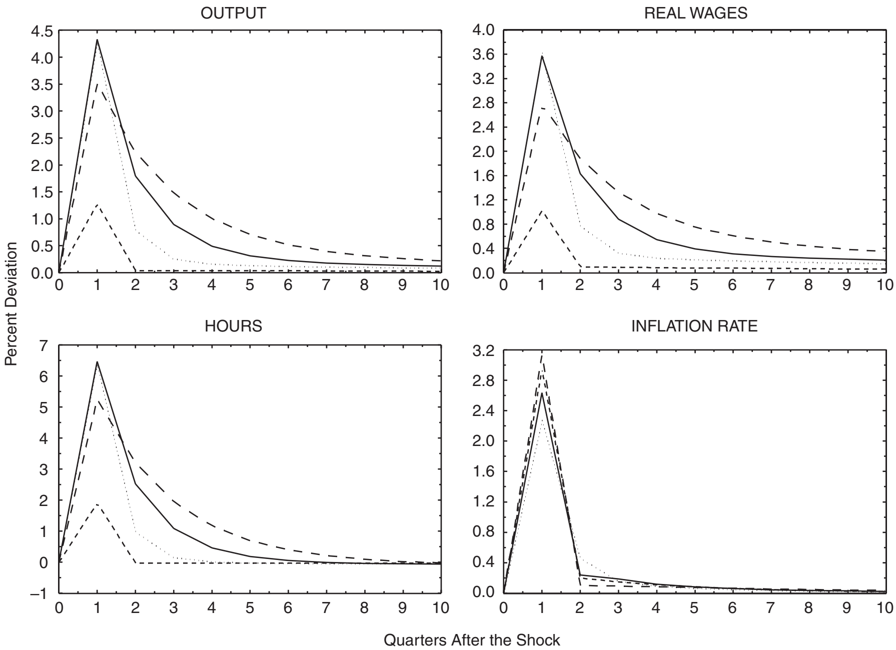

FIGURE 1 The effects of money-supply shocks in the four estimated models
NOTE: The impulse responses are computed for the SSP model (dashed line), the PCR model (dotted line), the PER model (large dashed line), and the PCER model (solid line).

(1997), Kim (2000), and Dib and Phaneuf (2001) find similar results for the U.S. and French economies.

The results presented in this subsection confirm the idea stressed by CKM (2000), in which a model with only sticky prices is unable to reproduce enough real effects from nominal disturbances. However, as stressed by Dib and Phaneuf (2001), if one follows Ball and Romer's (1990) original insight of combining nominal and real frictions, the extent of nominal price rigidity can be substantially magnified so that aggregate prices may adjust slowly in response to money supply shocks, inducing output persistence.

Figure 3 shows the impulse responses to a 1% positive technology shock. In SSP and PCR models, output, real wages, and hours immediately jump in response to the shock before returning gradually to their steady-state levels; however, in the presence of employment-adjustment costs (in the PER and PCER models), output and real wages increase gradually and hours worked slightly decline on impact.[16] On the other hand, as expected, inflation responds negatively to a positive supply shock. Its response is more substantial in the

16 Galí (1999) gives evidence that the decline in hours lasts approximately three quarters in the U.S. economy.

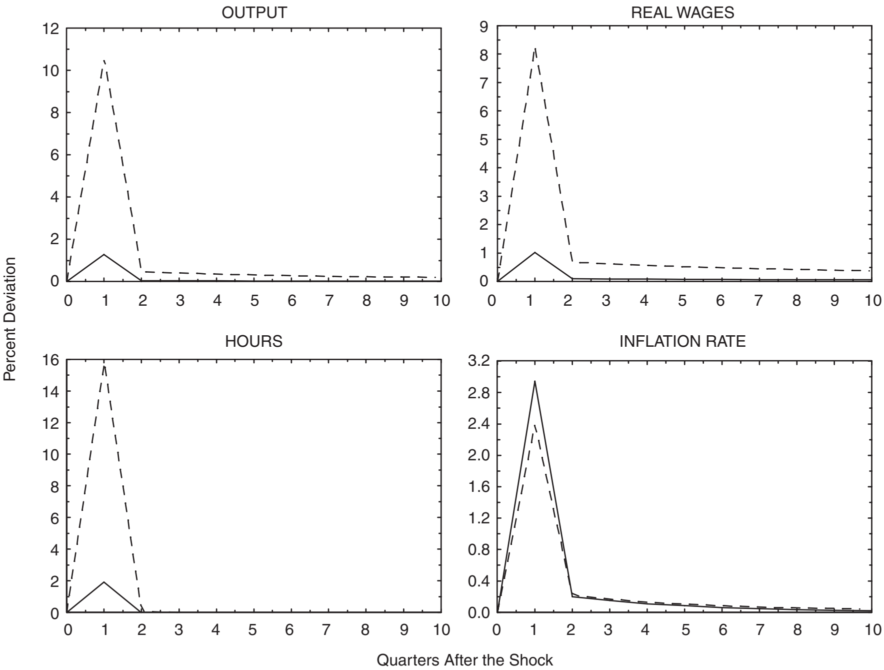

FIGURE 2 The effects of money-supply shocks in the SSP model with larger ϕ_p
NOTE: The impulse responses are computed for the SSP model with $\phi_p = 26.63$ (dashed line) and the SSP model with $\phi_p = 2.80$ (solid line).

PER and PCER models than in the models with perfectly flexible labour, but it exhibits little persistence in all models. By accommodating technology shocks, a significant fraction of the downward price pressure from the supply shock is offset by upward pressure from an increase in the money supply. Therefore, the decline in hours worked in models with employment-adjustment costs is less significant. Given that the amount of nominal price rigidity imparted by the nominal and real frictions is very substantial, the producing firms can meet their demand with less labour input because of the increase in labour productivity.

Figure 4 shows the impulse responses to a 1% positive money demand shock. Because the monetary authority responds to unfavourable money demand shocks by increasing the money supply, the responses of output, real wages, and hours are negative but systematically very small. Inflation positively responds to money demand shocks. Its response peaks two quarters after the shock and persists for more than two years. However, the deviation of inflation is quite small as well. Since all real variable responses to money demand shocks are systematically very small, one can conclude that the monetary authority successfully offsets the effects of money-demand shocks by

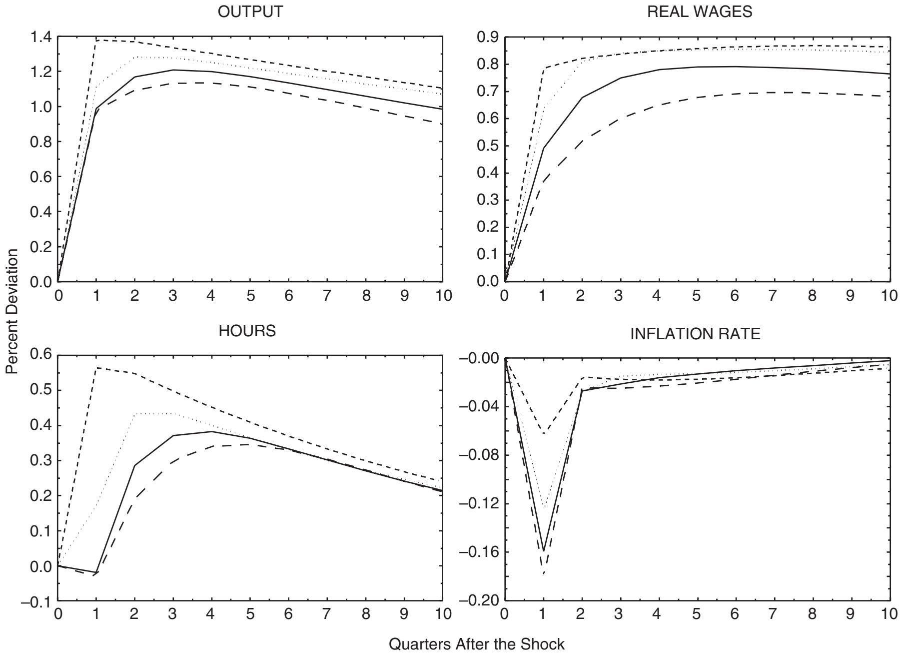

FIGURE 3 The effects of technology shocks in the four estimated models
NOTE: The impulse responses are computed for the SSP model (dashed line), the PCR model (dotted line), the PER model (large dashed line), and the PCER model (solid line).

responding countercyclically to these shocks. Ireland (1997) and Dib and Phaneuf (2001) find similar results for the U.S. economy.

5.2. Variance decomposition

Another way to look at the implications of the nominal and real rigidities is by computing the fractions of the forecast-error variance of detrended output, the inflation rate, and the money growth rate attributable to each type of shock. The results of this decomposition for several forecast horizons are reported in tables 2 to 5.

Table 2 gives the forecast-error variance decomposition of detrended output, inflation, and money growth in the SSP model, where there is only price rigidity. As shown in Panel A, money supply and money demand shocks explain very small fractions of output fluctuations even in the short term. However, technology shocks largely contribute to the variations of detrended output in the short and long term. This result matches the standard RBC models' predictions, in which technology shocks are the most important factor for output fluctuations in the short and long term. Panel B and Panel C show that the SSP model predicts that money supply shocks are the most important

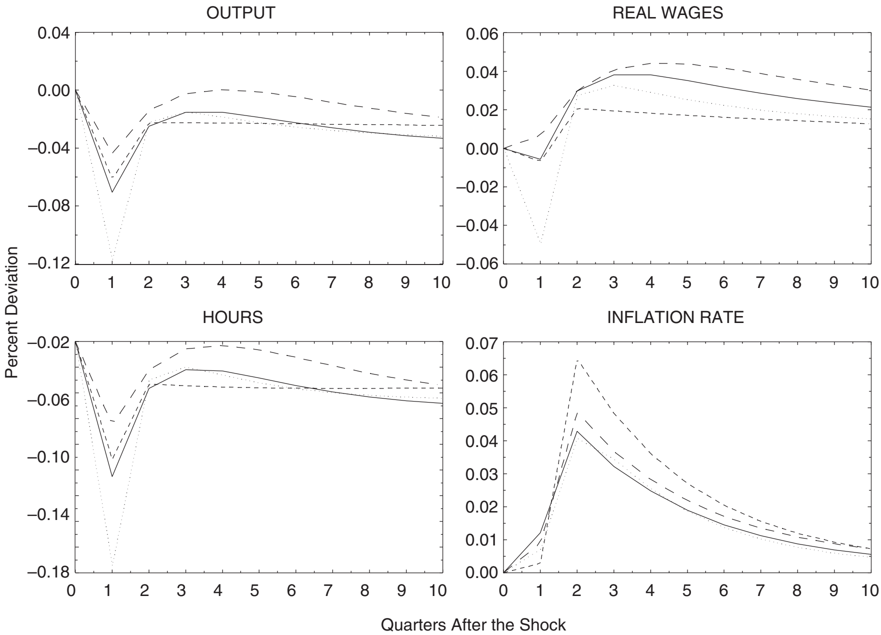

FIGURE 4 The effects of money-demand shocks in the four estimated models
NOTE: The impulse responses are computed for the SSP model (dashed line), the PCR model (dotted line), the PER model (large dashed line), and the PCER model (solid line).

source of inflation fluctuations in the short and long term, and money demand shocks explain about 94% of the forecast-error variance of the money growth.

Tables 2 to 5 report the forecast-error variance decomposition of detrended output, inflation, and money growth in the estimated models with nominal and real rigidities (PCR, PER, and PCER models, respectively). As shown in Panel A of the tables, money supply shocks contribute very substantially to the variance of detrended output at short horizons. At the one-quarter-ahead horizon, money supply shocks account for at least 37% of the forecast-error variance of detrended output. Furthermore, up to the one-year-ahead horizon, money supply shocks account for at least 17% of the forecast-error variance. Even at the ten-quarter-ahead horizon, money supply shocks still explain close to 7% of the variance of output. The counterpart, of course, is that technology shocks contribute less to short-run variation. At the one- and two-quarter-ahead horizons, technology shocks explain more than 47% and 65% of forecast-error variance of detrended output. By the tenth quarter, technology shocks account for at least 90%. This result is in contrast with the standard prediction of RBC models, which assumes that real disturbances explain almost all output fluctuations in the short and long terms. The contribution of money demand shocks is negligible, thus corroborating our impulse-response analysis.

TABLE 2
Forecast-error variance decomposition in the SSP model

		Percentage owing to		
Quarters	Variance	Money supply	Technology	Money demand
A. Detrended output				
1	0.000067	5.47	92.06	2.47
2	0.000128	2.86	95.67	1.46
4	0.000243	1.51	97.53	0.86
10	0.000532	0.70	98.59	0.71
50	0.001176	0.32	98.18	1.50
B. Inflation				
1	0.0000196	99.32	0.66	0.02
2	0.0000216	90.78	0.64	8.58
4	0.0000237	83.37	2.03	14.61
10	0.0000368	54.27	34.00	11.73
50	0.000252	7.97	89.96	2.07
C. Money growth				
1	0.00005	4.61	1.46	93.93
2	0.00007	4.61	1.46	93.93
5	0.00010	4.61	1.46	93.93
50	0.00011	4.61	1.46	93.93

TABLE 3
Forecast-error variance decomposition in the PCR model

		Percentage owing to		
Quarters	Variance	Money supply	Technology	Money demand
A. Detrended output				
1	0.00011	48.28	46.75	4.96
2	0.00018	30.54	66.31	3.15
4	0.00033	17.02	81.16	1.81
10	0.00080	7.12	91.87	1.00
50	0.00269	2.20	96.08	1.73
B. Inflation				
1	0.000015	95.78	4.09	0.12
2	0.000016	92.03	3.96	4.02
4	0.000018	88.34	4.35	7.30
10	0.000024	66.90	26.72	6.38
50	0.000153	11.04	87.42	1.54
C. Money growth				
1	0.00005	6.00	1.91	92.09
2	0.00007	6.00	1.91	92.09
5	0.00009	6.00	1.91	92.09
50	0.00010	6.00	1.91	92.09

TABLE 4
Forecast-error variance decomposition in the PER model

		Percentage owing to		
Quarters	Variance	Money supply	Technology	Money demand
A. Detrended output				
1	0.00006	37.39	60.90	1.71
2	0.00012	27.47	71.54	0.98
4	0.00024	16.90	82.59	0.50
10	0.00056	8.04	91.67	0.27
50	0.00119	4.02	92.90	3.08
B. Inflation				
1	0.000020	93.32	6.46	0.22
2	0.000022	87.41	6.16	6.43
4	0.000024	81.95	6.36	11.68
10	0.000037	57.41	31.82	10.76
50	0.000182	12.71	84.30	2.98
C. Money growth				
1	0.000049	3.97	0.31	95.72
2	0.000078	3.97	0.31	95.72
5	0.000104	3.97	0.31	95.72
50	0.000116	3.97	0.31	95.72

TABLE 5
Forecast-error variance decomposition in the estimated PCER model

		Percentage owing to		
Quarters	Variance	Money supply	Technology	Money demand
A. Detrended output				
1	0.00008	49.88	47.21	2.90
2	0.00015	33.40	64.74	1.86
4	0.00028	18.77	80.16	1.06
10	0.00068	8.05	91.16	0.76
50	0.00188	3.05	93.75	3.19
B. Inflation				
1	0.000016	93.34	6.22	0.43
2	0.000017	88.49	6.02	5.49
4	0.000019	84.60	6.17	9.23
10	0.000027	62.39	29.55	8.05
50	0.000152	11.68	85.91	2.40
C. Money growth				
1	0.000048	4.62	0.97	94.41
2	0.000075	4.62	0.97	94.41
5	0.000104	4.62	0.97	94.41
50	0.000105	4.62	0.97	94.41

Panel B in tables 2 to 5 show the forecast-error variance decomposition of the inflation rate. In this case, the models combining nominal and real rigidities predict that money supply shocks are the important factor determining movements in the inflation rate at short and longer horizons. The money supply shock accounts for nearly 93% of the variance of the inflation rate at the one-quarter-ahead horizon, and it still contributes at least 57% at the ten-quarter-ahead horizon. Technology shocks negligibly contribute to the variance of inflation in the short term, with only about 4–6% at the one- and four-quarter-ahead horizons, but they substantially contribute to the inflation variance in the long term, with about 27% and 87% at the ten- and fifty-quarter-ahead horizons, respectively. The contribution of money demand shocks is negligible.

Panel C in tables 2 to 5 show that more than 92% of the money growth variance is explained by money demand shocks. Similar results are found by Rotemberg and Woodford (1997), Ireland (1997), and Dib and Phaneuf (2001) for the U.S. economy.

6. Conclusion

Ever since the monumental study by Friedman and Schwartz (1963), it has been repeatedly confirmed that nominal disturbances exert a significant impact on economic fluctuations, at least in the short term. Recently developed models, resting on the optimizing behaviour of rational agents in a dynamic, stochastic, general-equilibrium environment, emphasize the role of nominal price rigidity. These models, however, generate only weak persistence of real variables in response to money supply shocks, which is in contrast to evidence indicating that real effects of monetary policy shocks are highly persistent.

In a static framework of price-setting agents, Ball and Romer (1990) have shown that the degree of nominal rigidity arising from a given menu cost increases with the degree of real rigidity, which produces larger money non-neutralities. Following this original intuition of combining nominal and real rigidities, this paper extends Ireland's (1997) work by developing and estimating a DSGE model with nominal and real rigidities for the Canadian economy. Nominal and real rigidities are modelled as the quadratic costs of adjusting prices, capital, and/or employment. The structural parameters that are essential for the identification of transmission channels leading to high real persistence have been estimated by a maximum-likelihood procedure with a Kalman filter and using Canadian quarterly data from 1976Q1 to 2000Q4.

According to the estimation results, the combination of nominal and real rigidities induces higher estimated values of the price-adjustment cost parameter, which, in turn, implies a greater amount of nominal price rigidity, and generates higher persistence of real variables in response to money supply shocks. Thus, combining nominal and real rigidities can substantially magnify the dynamic propagation of money supply shocks in a DSGE environment. Furthermore, the simulation results suggest that the monetary authority has accommodated technology shocks and has successfully offset the real effects of money-demand shocks by actively responding to technology and money demand shocks. Nevertheless, despite the nominal and real rigidities, inflation continues to adjust very rapidly and the model is unable to generate larger inflation persistence in response to different shocks, as observed in the data.

Since Canada is a small open economy, the effects of nominal and real world shocks on its domestic economy should be considered. As such, future work consists of extending this framework to develop and estimate an optimizing DSGE model for a small open economy.

Appendix A: Household's first-order conditions

$$c_t: \quad \frac{c_t^{-\frac{1}{\gamma}}}{c_t^{\frac{\gamma-1}{\gamma}} + b_t^{\frac{1}{\gamma}}(M_t/p_t)^{\frac{\gamma-1}{\gamma}}} - \lambda_t = 0; \tag{A1}$$

$$M_t: \frac{b_t^{\frac{1}{\gamma}}(M_t/p_t)^{-\frac{1}{\gamma}}}{c_t^{\frac{\gamma-1}{\gamma}} + b_t(M_t/p_t)^{\frac{\gamma-1}{\gamma}}} - \lambda_t + \beta E_t\left(\frac{p_t\lambda_{t+1}}{p_{t+1}}\right) = 0; \tag{A2}$$

$$h_t: \quad \frac{\eta}{1-h_t} - \lambda_t\frac{W_t}{p_t} = 0; \tag{A3}$$

$$k_{t+1}: \beta E_t\left[\frac{\lambda_{t+1}}{\lambda_t}\left(\frac{R_{t+1}}{p_t} + \frac{\phi_k}{2}\left(\frac{i_{t+1}}{k_{t+1}}\right)^2 + (1-\delta)\left(1+\phi_k\frac{i_{t+1}}{k_{t+1}}\right)\right)\right] - \phi_k\frac{i_t}{k_t} - 1 = 0, \tag{A4}$$

in addition to the budget constraint and capital accumulation equations.

Appendix B: Intermediate-goods-producing firm's first-order conditions

$$k_t: \quad \alpha\frac{y_{jt}}{k_{jt}}\frac{\xi_t}{\lambda_t} - \frac{R_t}{p_t} = 0; \tag{B1}$$

$$h_t: (1-\alpha)\frac{y_{jt}}{h_{jt}}\frac{\xi_t}{\lambda_t} - \frac{W_t}{p_t} - \phi_h\left(\frac{h_{jt}}{h_{jt-1}} - 1\right)\frac{y_t}{h_{jt-1}} + \beta\phi_h E_t\left[\left(\frac{h_{jt+1}}{h_{jt}} - 1\right)\frac{h_{jt+1}y_{t+1}}{h_{jt}^2}\frac{\lambda_{t+1}}{\lambda_t}\right] = 0 \tag{B2}$$

$$p_{jt}:\frac{\xi_t}{\lambda_t}-\frac{\theta-1}{\theta}\frac{p_{jt}}{p_t}-\frac{\phi_p}{\theta}\left(\frac{p_{jt}}{p_{jt-1}}-1\right)\frac{p_{jt}}{p_{jt-1}}\frac{y_t}{y_{jt}} + \frac{\beta\phi_p}{\theta}E_t\left[\left(\frac{p_{jt+1}}{p_{jt}}-1\right)\frac{p_{jt+1}}{p_{jt}}\frac{\lambda_{t+1}}{\lambda_t}\frac{y_{t+1}}{y_{jt}}\right]=0; \tag{B3}$$

$$\xi_t:A_t k_{jt}^{\alpha}\left(g^t h_{jt}\right)^{1-\alpha}-\left(\frac{p_{jt}}{p_t}\right)^{-\theta}y_t=0. \tag{B4}$$

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