Factor-Market Structure, Shifting Inflation Targets and the New Keynesian Phillips Curve*

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Abstract

This paper evaluates the ability of the New Keynesian Phillips curve to capture important features of aggregate Canadian consumer price inflation. In contrast to the earlier New Keynesian Phillips curve literature we modify three assumptions. First, we relax the assumption of a constant and credible historical inflation target. Second, we replace the usual proxy for marginal cost, labour's share of income, with an open-economy definition that allows for non-Cobb-Douglas production, adjustment costs to labour, and an explicit role for imported intermediate goods. Finally, in contrast to the standard assumption of a rental market for capital, we follow Sbordone (2002) and assume that capital is firm specific. The model is estimated using a version of the simulated method of moments. Overall, we find that the first two modifications to the standard set-up lead to a better fit of the data while the third change yields a more reasonable average duration between price reoptimizations. The model, however, continues to require the presence of lagged inflation to match the persistence found in aggregate Canadian inflation data.

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1 Introduction and Summary

Understanding the economic forces that drive inflation dynamics is important for a monetary authority, especially for those practicing inflation targeting. The recent economics literature has used versions of the so-called New-Keynesian Phillips curve in an effort to improve our understanding of inflation dynamics. The canonical New Keynesian Phillips curve (NKPC) links current inflation to real marginal cost and the expectation of future inflation, and arises from the Calvo model of staggered price-setting behaviour under certain assumptions (see Yun (1996) and Woodford (1996)). The main advantage of the NKPC approach over more traditional reduced-form approaches is that the former has a theoretical foundation and, therefore, a clear structural interpretation. While the ability of the canonical NKPC to deliver a structural interpretation of inflation dynamics is important, its empirical support has been weak (for an example based on Canadian data see Guay, Luger and Zhu (2002)). Countless variations of the New Keynesian Phillips curve have been proposed in an effort to improve its congruence with the data. The most notable variations are, perhaps, the ones proposed by Gali and Gertler (1999) and Christiano et al. (2005) which effectively add lagged inflation to create a "hybrid NKPC". Gali and Gertler motivate the lagged inflation term by the presence of firms that use rule-of-thumb pricing strategies whereas Christiano et al. appeal to dynamic price indexation. Notwithstanding the way lagged inflation is introduced into these models, the main aim of the lagged dependent variable is to address previously noted empirical shortcomings of the canonical NKPC. The empirical evidence based on Canadian data, however, has been mixed. Khan and Gagnon (2005), for instance, find evidence in favour of the hybrid NKPC whereas Nason and Smith (2004) statistically reject the model.

In this paper, we take another look at the ability of the NKPC with partial dynamic price indexation to capture key features of Canadian inflation data. Our study, however, differs from previous research along three important dimensions. In particular, we relax three assumptions often made in the NKPC literature, *viz.*, (i) constant (and observable and credible) inflation target; (ii) labour's share of income as a measure of marginal cost; and (iii) rental market for capital. We believe the empirical performance of the NKPC is an especially important question since the behaviour of inflation dynamics has important implications for monetary policy, and in particular for how central banks should react to real events while maintaining its inflation target. For instance, the degree to which inflation is a predetermined variable is critical to the question of how forward looking monetary policy should be (see Batini and Nelson (2001)).

A natural question that arises from this exercise is why we choose these three particular assumptions and not others. It is certainly possible that other assumptions are even more important to our understanding of inflation dynamics within the NKPC framework, but we focus on the three aforementioned assumptions since there is strong empirical evidence against these restrictions and, we are able to readily address them in a reasonable manner. First, as already mentioned, an important maintained assumption of previous empirical NKPC studies is that the monetary policy regime has been constant over the sample period of estimation. We relax the assumption of a constant historical inflation target since empirical evidence suggests it is an unrealistic assumption, at least for the Bank of Canada.

Second, we replace the usual proxy for marginal cost, labour's share of income, with an open-economy definition that allows for non-Cobb-Douglas production, adjustment costs to labour, and an explicit role for imported intermediate goods. There is much evidence to support our approach. Empirical evidence reported in Gilchrist and Williams (2000) for the United States, and Amano and Wirjanto (1997) for Canada suggests that capital and labour are less substitutable than the Cobb-Douglas production function admits, suggesting a more general production function may be a more appropriate description of short-run production. With respect to labour adjustment costs, there is an extensive literature documenting the presence of statistically significant costs of labour adjustment. Moreover, Krause and Lubik (2003) find, in the context of a New Keynesian model with search and matching frictions in the labour market, that labour share is not a good proxy for real marginal cost. An explicit role for imported intermediate goods may be motivated by real world observation that final Canadian goods have a large imported input component. As well, McCallum and Nelson (2000) find an important role for imported intermediate goods for the ability of a small open economy model to replicate data-based impulse response functions, and Batini, Jackson and Nickell (2005) detail the importance of import prices for measuring marginal cost in a small open economy.

Third, we abstract from the standard assumption of a rental market for capital and assume the presence of firm-specific capital. In our work, we treat the capital stock of each firm as invariant to their relative price (Sbordone (2002) and Gali, Gertler and Lopez-Salido (2001) also treat firm-specific capital in the same manner). While this assumption abstracts from the influence of endogenous capital accumulation, Eichenbaum and Fisher (2004) find only a small effect on the degree of real rigidity when moving from a specification with empirically reasonable capital adjustment costs to one where the capital stock is exogenously given. Thus, the assumption of relative price invariance does not appear to be of first-order importance for the degree of strategic complementarity among the pricing decisions of different firms. This is an important point since the degree of strategic complementarity influences the sensitivity of inflation to fluctuations in marginal cost.

Finally, our version of the NKPC is estimated using a simulated method of moments estimator similar to that proposed by Smith (1993). This procedure compares the properties of the reduced-form VAR representation of the structural model to an unconstrained VAR. One notable advantage of these two estimation methods is that they allow us avoid identification problems that often plague instrumental variables (that is, GMM) estimation of NKPC models (see, for example, Nason and Smith (2004)).

The remainder of the paper is organized as follows. After presenting the structure of the price-setting model in Section 2, we describe and use two approaches for estimating time-varying inflation targets in Section 3. In Section 4 we review the estimation methodology and in Section 5 we report the empirical results. In particular, we examine the implications of the parameter estimates for the average duration between price *reviews,* or what we will refer to as reoptimizations, as well as the sensitivity of inflation to movements in marginal cost. Also, we test the ability of our version of the NKPC model to match important vector autocorrelations found in the data and we compare its forecasting performance relative to two often used inflation forecasting models. In Section 6 we offer concluding remarks and suggestions for future work.

2 A Small Open Economy Model

In this section we formulate a price-setting framework incorporating a non-constant inflation target, firm-specific capital and a constant-elasticity of substitution (CES) production technology that includes imported intermediate goods and labour adjustment costs. Within this framework, prices are determined according to Calvo (1983) with partial dynamic price indexation. Therefore, our framework includes two real rigidities: labour adjustment costs and firm-specific capital. However, we focus principally on the latter since it has important implications for the link between marginal cost and inflation, and the estimated average length of price contracts. One potentially-key real rigidity that we do not include in the framework is non-constant elasticity of demand (see Kimball (1995)). Eichenbaum and Fisher

(2004) and Coenen and Levin (2004) have recently explored the importance of a high degree of curvature in the firm's demand function for reducing the sensitivity of prices to changes to firms' marginal cost. In preliminary work, we find that, like Coenen and Levin, the dampening of the response of inflation to fluctuations in marginal cost arising from firm-specific capital is sufficient to induce our model to match important inflation moments. Thus, the absence of non-constant elasticity of demand in our price-setting framework does not appear to be a gross omission.[1]

2.1 Final Goods Production

Final goods in our economy, Z_t, are produced by a representative, perfectly competitive firm combining a continuum of intermediate finished goods, Z_{it} $i \in [0,1]$, using the technology

$$Z_t = \left[\int_0^1 Z_{it}^{\frac{\epsilon-1}{\epsilon}} di \right]^{\frac{\epsilon}{\epsilon-1}}, \tag{1}$$

and charges the price, P_t, according to

$$P_t = \left[\int_0^1 P_{it}^{1-\epsilon} di \right]^{\frac{1}{1-\epsilon}}. \tag{2}$$

Final goods can be thought of as either being consumed or invested in our model economy. Thus, consumption and investment prices are the same and equal to P_t. However, given that the focus of this paper is on the consumer price index, P_t will correspond to the CPI excluding the eight most volatile items[2] (hereafter the CPIX) for all empirical work. Our choice of the CPIX reflects its role an the operational measure of underlying or trend inflation for the Bank of Canada when setting policy.

Profit maximization implies the following demand function by the aggregator for the i^{th} firm's output

$$Z_{it} = \left(\frac{P_{it}}{P_t} \right)^{-\epsilon_t} Z_t. \tag{3}$$

[1] In addition there is a lack of evidence about the degree of curvature in the firm's demand function making calibration of this parameter extremely difficult.

[2] The 8 items are; fruit, vegetables, gasoline, fuel oil, natural gas, mortgage interest, inter-city transportation and tobacco products.

2.2 Production Technology and Marginal Cost

We assume a continuum of monopolistically-competitive firms, indexed by i, $i \in [0,1]$, that each produce a differentiated final good using a CES production technology in labour, L_{it}, capital, K_{it}, and imported inputs, M_{it}

$$Z_{it} = \left(\delta_1^{\frac{1}{\sigma}} \left(A_t L_{it}\right)^{\frac{\sigma-1}{\sigma}} + \delta_2^{\frac{1}{\sigma}} \left(K_{it}\right)^{\frac{\sigma-1}{\sigma}} + \left(1-\delta_1-\delta_2\right)^{\frac{1}{\sigma}} \left(M_{it}\right)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}} - \Omega_{i,t}, \tag{4}$$

and charge a price, P_{it}, for their good that maximizes present and expected future discounted profits. A_t is labour augmenting technology. Imports are included as a factor of production since approximately 20 per cent of Canadian consumption goods are imported. The parameters δ_1 and δ_2 are increasing functions of the shares of labour and capital in production, and the elasticity of substitution among the three factors is assumed equal and constant at σ, $\sigma \neq 1$. Empirical implementations of the NKPC have often used labour's share of output as a proxy for marginal cost (see, for example, Gali and Gertler (1999) for US data and Gagnon and Khan (2005) for Canadian data) when modelling the GDP deflator. While labour share is a convenient proxy for marginal cost, there is good reason to believe that it understates fluctuations in true marginal cost. Studies using Canadian data (see, for example, Amano and Wirjanto (1997)) place this elasticity between 0.3 to 0.6 suggesting a greater degree of complementarity between capital and labour than admitted by the Cobb-Douglas production function. Thus, in an effort to capture such complementarity, we use a CES production function to describe short-run Canadian production.

When purchasing labour and imports, firms are assumed to take nominal wage, W_t, and price of imports, P_{mt}, as given. However, we assume that varying the level of employment is costly to the firm, and the costs, governed by the parameter χ, take the form of lost labour productivity. Specifically, we assume a quadratic penalty function in the growth rate of employment

$$\Omega_{i,t} = \frac{Z_t \chi}{2} \left(\frac{L_{it}}{L_{i,t-1}} - 1 \right)^2, \tag{5}$$

so in steady state $\Omega = 0$. Profit maximization on the part of the firm, subject to equations (3, 4 and 5) imply the following first-order conditions for imported inputs and labour

$$0 = \left(\frac{(1-\delta_1-\delta_2)\, Z_{i,t}}{M_{i,t}}\right)^{\frac{1}{\sigma}} - \frac{P_{mt}}{\lambda_{i,t}}, \tag{6}$$

$$0 = \left\{ \begin{array}{c} \lambda_{i,t}\left(\frac{\delta_1 Z_{i,t}}{L_{i,t}}\right)^{\frac{1}{\sigma}} A_t^{\frac{\sigma-1}{\sigma}} - \frac{Z_{i,t}\lambda_{i,t}\chi}{L_{i,t-1}}\left(\frac{L_{i,t}}{L_{i,t-1}}-1\right) \\ +\mathbf{E}_t \frac{\lambda_{i,t+1}Z_{i,t+1}\chi}{(1+R_{i,t})L_{i,t}^2} L_{i,t+1}\left(\frac{L_{i,t+1}}{L_{i,t}}-1\right) - W_t \end{array} \right\}. \tag{7}$$

Expressed in terms of *real* marginal cost and labour's share of output, $s_{i,t}$, we have

$$\frac{\lambda_{i,t}}{P_{i,t}} = \left\{ \frac{s_{i,t}}{\delta_1^{\frac{1}{\sigma}}\left(\frac{A_t L_{i,t}}{Z_{i,t}}\right)^{\frac{\sigma-1}{\sigma}} - \chi\left(\frac{L_{i,t}}{L_{i,t-1}}\left(\frac{L_{i,t}}{L_{i,t-1}}-1\right) + \kappa_{t+1}\left(\frac{L_{i,t+1}}{L_{i,t}}-1\right)\right)} \right\},$$

where the denominator is the elasticity of current and future production with respect to time-t labour and

$$\kappa_{t+1} \equiv \frac{\lambda_{i,t+1}L_{i,t+1}Z_{i,t+1}}{\lambda_{i,t}L_{i,t}Z_{i,t}\,(1+R_t)}.$$

Linearizing around a steady state characterized by $L_{i,t} = \overline{L}$ and $\overline{\kappa} = 1$ (the real interest rate equals the real growth rate of the economy) we obtain

$$\widehat{\lambda}_{i,t} = \Theta\left(\widehat{s}_t - \frac{\chi}{s_L}\left(\Delta^2\mathbf{E}_t\widehat{L}_{i,t+1}\right)\right) + \Lambda\widehat{z}_{k,i,t} + (1-\Theta)\,\widehat{p}_{m,t}, \tag{8}$$

where $\widehat{z}_{k,t} = \widehat{Z}_{i,t} - \widehat{K}_t$, and $\widehat{\lambda}_{i,t}$ captures the percentage deviation of *real* marginal cost from its steady state and

$$\Theta = \frac{s_L}{s_L + (1-\sigma)\,(1-s_L-s_K)},$$

$$\Lambda = \frac{1-\sigma}{\sigma}\frac{s_K}{s_L + (1-\sigma)\,(1-s_L-s_K)}.$$

where s_L and s_k are labour and capital share parameters, respectively. Now consider a simple autoregressive model for computing $\mathbf{E}_t\Delta\widehat{L}_{i,t+1}$

$$\Delta\widehat{L}_{t+1} = \rho_1\Delta\widehat{L}_t + \rho_2\Delta\widehat{L}_{t-1} + u_t,$$

which we estimate by ordinary least squares using Canadian employment data from 1980 to 2004.[3] Equation (8) can now be re-written in terms of

[3] The choice of two lags is based on the AIC criterion.

variables observed at time t

$$\widehat{\lambda}_{i,t} = \Theta\left(\widehat{s}_{i,t} - \frac{(\rho_1 - 1)\,\chi}{s_L}\left(\Delta\widehat{L}_{i,t} + \frac{\rho_2}{\rho_1 - 1}\Delta\widehat{L}_{i,t-1}\right)\right) + \Lambda\widehat{z}_{k,i,t} + (1-\Theta)\,\widehat{p}_{m,t}. \tag{9}$$

Having now derived a general expression for marginal cost, it is interesting to note that if $\sigma = 1$ and $\chi = 0$, we obtain $\widehat{\lambda}_{i,t} = \widehat{s}_{i,t}$ and with no imports in production $\widehat{s}_{i,t}$ corresponds to labour's share of nominal GDP, the typical proxy for real marginal cost.

2.3 New Keynesian Phillips Curve Equation

In this section, we describe a log-linearized inflation equation based on Calvo (1983) price setting augmented with firm-specific capital and partial dynamic price indexation. The latter assumption implies a firm that cannot re-optimize its price follows the rule

$$P_{it} = P_{i,t-1}\,(1 + \pi_{t-1})^{\gamma}\,. \tag{10}$$

A number of researchers have argued that this kind of modification to the canonical NKPC results in a more realistic specification. Christiano et al. (2005) and Giannoni and Woodford (2003) argue that a model with $\gamma = 1$ improves its ability to reproduce key moments in the data. Smets and Wouters (2003) treat γ as a free parameter and, in contrast, conclude that the best-fitting value of γ is around 0.6. Smets and Wouters (2003) show that the Calvo model with partial dynamic indexation, indexed by γ with $\gamma \in (0,1)$, may be written as

$$\widehat{\pi}_t = \frac{\gamma}{1+\beta\gamma}\widehat{\pi}_{t-1} + \frac{\beta}{1+\beta\gamma}\widehat{\pi}_{t+1} + \phi\widehat{\lambda}_t, \tag{11}$$

where $\widehat{\pi}_t = \pi_t - \pi_t^T$, $\pi_t = \ln(P_t/P_{t-1})$, P_t is the Canadian consumer price index excluding the eight most volatile components (CPIX) and π_t^T is steady-state inflation or the Bank of Canada's inflation target. Equation (11) says that the deviation of inflation from its target (i.e. the inflation gap, $\widehat{\pi}_t$) depends on past and expected future inflation deviations and on current real marginal cost. When γ, the parameter governing the magnitude of indexation, is zero, the equation reverts to its canonical form. Conversely, when γ is positive, the degree of indexation to lagged inflation provides a measure of the degree of persistence in Canadian inflation dynamics after accounting for shifts in the inflation target and the persistence in real marginal cost. In the empirical section, we conduct formal tests to determine whether γ is statistically different from zero.

An important feature to note is that the only difference between the log-linearized inflation equation in the homogenous versus firm-specific capital case pertains to the structural relationship between inflation and marginal cost.[4] While the form of the equation in both cases is identical, the difference lies in the mapping between the reduced-form parameter governing the effect of marginal cost on inflation and the structural parameters. Under the capital rental market assumption, the elasticity of inflation with respect to changes in marginal cost depends primarily on γ and the fraction of firms that re-optimize prices within a period, $1-\theta$, or more specifically[5]

$$\phi = \frac{(1-\theta)(1-\beta\theta)}{(1+\beta\gamma)\theta}.$$

Under the assumption of firm-specific capital, ϕ is a function of a broader set of structural parameters

$$\phi = \eta \cdot \frac{(1-\theta)(1-\beta\theta)}{(1+\beta\gamma)\theta}; \qquad \eta < 1. \tag{12}$$

where η captures the difference between average and firm-specific marginal cost. Furthermore, if we make the assumption that firms are unable (exogenous capital) or unwilling (due to adjustment costs on investment that approach infinity) to change their capital stock in response to changes in economic conditions then

$$\eta = \left\{ \frac{\sigma\mu s_L}{\sigma\mu s_L + \epsilon(1-\mu s_L)} \right\}, \tag{13}$$

where μ is steady-state mark-up of price over marginal cost, and ϵ represents the demand elasticity by the aggregator. Effectively, η steepens the marginal cost curve at the firm level, dampening the effect of marginal cost movements on inflation. We discuss this effect and its implications in greater detail below.

[4] Discussions of the role pf firm-specific capital are provided in Eichenbaum and Fisher (2004), Altig et al. (2004) and Woodford (2005).

[5] In a world with indexation, we cannot interpret θ as the probability that a given firm keeps its nominal price fixed since all prices change every period. Rather it is interprettable as the probability that a firm will index its price to lagged inflation rather than choosing a price that optimizes expected profits.

3 Estimating the Inflation Target

Numerous observers have noted changes in Canadian monetary policy over the post Bretton Woods period. Atoian (2004), for instance, estimates the parameters of a forward-looking structural model jointly with the preference parameters of the Bank of Canada's objective function and finds evidence consistent with three policy regimes with different inflation targets over the 1970 to 2002 sample period. Moreover, Nelson (2005) provides a lucid quantitative and graphical overview of Canadian monetary policy in the 1970s and 1980s based on newspaper articles and policy makers' statements. Nelson finds, *inter alia*, evidence suggesting changes in monetary policy regime over time. Perhaps the most convincing piece of evidence is a 2000 lecture given by then Bank of Canada Governor Thiessen that described the evolution of Canadian monetary policy. In the lecture, Governor Thiessen identifies three monetary policy regimes since 1971: (i) Stagflation and monetarism, 1971-81; (ii) the search for a new nominal anchor, 1982-90; and (iii) inflation targets, 1991-present. Taken together, there is much evidence suggesting that the Bank of Canada's implicit inflation target has shifted over time.

The evidence suggests the assumption of a constant inflation target is untenable and so it is replaced with a target that varies over time. It should be noted that relaxing the assumption of a constant inflation target has important implications for inflation dynamics. Researchers have found recently that the lagged inflation term needed in canonical NKPC models to help explain key features of aggregate inflation data may reflect shifts in the monetary policy regime rather than "structural" backward-looking behaviour. Indeed, Coenen and Levin (2004), Cogley and Sbordone (2005) and Kozicki and Tinsley (2002) argue that it is essential to account for shifts in monetary policy to avoid finding spurious evidence of inflation persistence. Coenen and Levin find that a canonical NKPC is able to account for the persistence of German inflation once shifts in monetary policy are taken into account. As well, Kozicki and Tinsley (2002) report, *inter alia*, empirical evidence suggesting that shifts in monetary policy regime and less than full policy credible have contributed importantly to observed persistence of US and Canadian inflation.[6]

While assuming a non-constant inflation target adds a degree of potential realism to our model, it requires us to construct a measure of an implied inflation target. We use two approaches to construct such a variable and

[6] Andolfatto and Gomme (2003) find similar results in the context of a DSGE model.

describe each method in turn.

3.1 Moving Endpoints Method (MEP)

The first method is the VAR with moving endpoints approach (hereafter MEP) developed in Kozicki and Tinsley (1998). Briefly, the method entails estimating a VAR with variables in deviations from steady-state form so any nonstationarity arising in the VAR is attributed to shifts in the steady state. Following Kozicki and Tinsley (2002), we assume that only the steady-state of inflation displays nonstationary behaviour. The reduced-form model assumes that the dynamics of the variables under consideration are well described by a j-lag VAR. In each quarter, variation in the inflation target is assumed to be an independent normal innovation. The reduced-form is given by

$$\begin{bmatrix} \pi_t \\ \lambda_t \\ R_t \end{bmatrix} = \sum_{i=1}^{j} \mathbf{A}_i \begin{bmatrix} \pi_{t-i} \\ \lambda_{t-i} \\ R_{t-i} \end{bmatrix} + \left(\mathbf{I} - \sum_{i=1}^{j} \mathbf{A}_i \right) \begin{bmatrix} \overline{\pi}_t \\ \overline{\lambda} \\ \overline{r} + \overline{\pi}_t \end{bmatrix} + \mathbf{u}_t. \qquad (14)$$

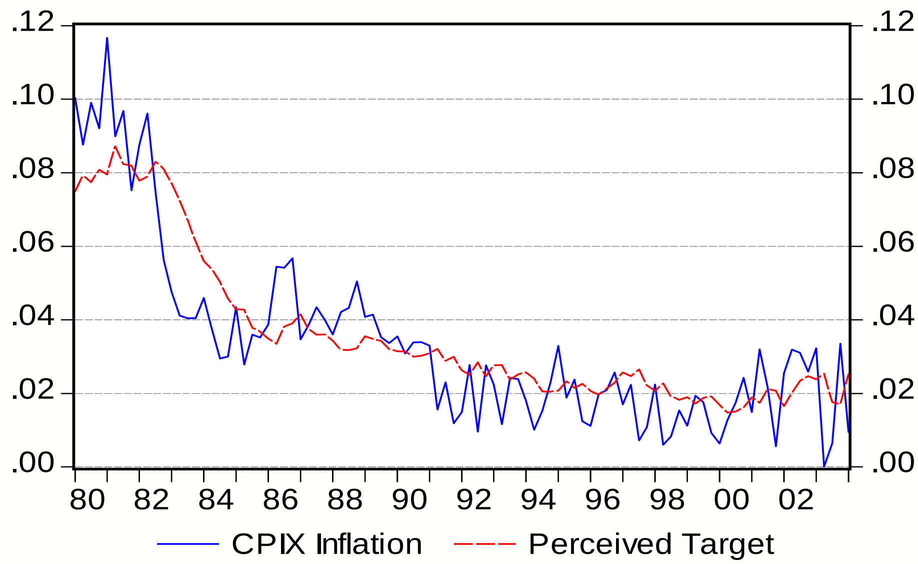
$\overline{r}$ is interpreted as the steady-state real interest rate and the inflation target follows a random walk process

$$\overline{\pi}_t = \overline{\pi}_{t-1} + \nu_t, \qquad (15)$$

with $\mathbf{E}(\nu_t u_{it}) = 0 \;\; i = 1, 2, 3$. The VAR and inflation-target innovations are assumed to serially uncorrelated and uncorrelated with each other. Owing to the unobserved state variable π_t^T, we use Kalman filtering methods to estimate the model. **Figure 1** shows actual inflation and the implied inflation target from the VAR with the moving endpoints approach. The estimated inflation target is the unsmoothed estimate of the state variable from the Kalman filter. The estimated inflation target follows the path of actual inflation reasonably well. Interestingly, the implied inflation target is higher than actual inflation during the disinflation of 1981-82, suggesting that the Bank of Canada did not have full credibility in its efforts to reduce inflation. The estimated inflation target also appears to capture the announced downward inflation target path from 3 per cent to 2 per cent (1992 to 1995) as well as the current 1 to 3 per cent inflation targeting range.

Figure 3 shows a plot of real marginal cost and the MEP-based inflation gap. We see here that both series broadly move together, particularly over the early and late 1980s and early 1990s. The full-sample correlation is 0.45.

Figure 1: MEP-Based Perceived Inflation Target



3.2 Staff Projection Method (SEP)

Our second method exploits our access to Staff projection data and attempts to make efficient use of this information to calculate an implied inflation target over history.[7] It should be emphasized that there is an important distinction between a projection and a forecast. An inflation forecast attempts to answer the question: What will inflation be in k-periods? In contrast, a Bank of Canada Staff projection tries to answer the question: What will the monetary authority need to do to achieve a particular level of inflation over a certain period? Thus, Staff inflation projection data appears to be an appropriate variable to use with the current methodology.

We begin by positing that the Bank of Canada has set policy in a manner broadly consistent with a simple rule of the form

$$R_t = \zeta_t R_{t-1} + \mathbf{E}_{t-1}\left(1-\zeta_t\right)\left(\overline{r} + \pi_t + \omega_{1,t}\left(\pi_t - \overline{\pi}_t\right) + \omega_{2,t}\widetilde{y}_t + \omega_{3,t}\Delta z_t\right) + \varepsilon_t, \tag{16}$$

where $\overline{r}$ is the steady-state real interest rate (assumed to be constant), $\widetilde{y}_t$ is the output gap and and Δz_t is the growth rate of the real exchange rate.

[7] We thank Jean Boivin for suggesting this idea.

It is important to note the information set available to the central bank when setting the nominal interest rate at time t. We assume that rates are set before the time-t shocks are observed, which we view as realistic given the lag associated with the release of Statistics Canada data. In addition, we make the convenient, but perhaps more contentious assumption that the Bank of Canada calculated potential GDP using an HP filter over history. In addition, we restrict the information given to the filter such that the trend value for output at time $t-1$ only uses GDP data up to that point in time. We then close the system with an unrestricted VAR for the relevant variables needed in order to set the interest rate and forecast future inflation. That is, we assume that the staff forecasts can be well-captured by a small-dimension VAR(p) in the variables of interest $\mathbf{X}_t' = \{1, \pi_t, \widetilde{y}_t, \Delta z_t\}$

$$\mathbf{X}_t = \sum_{i=1}^{p} \mathbf{A}_{i,t}\mathbf{X}_{t-i} + \mathbf{u}_t \tag{17}$$

where 1 is a simply a time series of ones intended to capture the constant. If we augment (17) with our "structural" monetary policy rule we obtain

$$\mathbf{E}_{t-1}\mathbf{B}_{0,t}\mathbf{X}_t = \sum_{i=1}^{p} \mathbf{B}_{i,t}\mathbf{X}_{t-i}$$

with

$$\mathbf{B}_{0,t} = \begin{bmatrix} \mathbf{I}_{4\times 4} & & & & \mathbf{0}_{4\times 1} \\ \xi_{1,t} & \xi_{2,t} & \xi_{3,t} & \xi_{4,t} & 1 \end{bmatrix}; \quad \mathbf{B}_{1,t} = \begin{bmatrix} & & \mathbf{A}_1 & & \\ 0 & 0 & 0 & 0 & \zeta_t \end{bmatrix}.$$

Of course, at this point in time we have said nothing about how to identify the bottom row of $\mathbf{B}_{0,t}$. Our methodology for doing is as follows; suppose we wish to compute the central bank's target for period s, we would first estimate the 5-variable reduced-form VAR(p) $\mathbf{X}_t' = \{1, \pi_t, \widetilde{y}_t, \Delta z_t, R_t\}$, given as

$$\mathbf{X}_{s-1} = \sum_{i=1}^{p} \mathbf{\Phi}_{i,s-1}\mathbf{X}_{s-i-1} + \mathbf{e}_{s-1},$$

on data up to and including period $s-1$. Next, we define the vector

$$\mathbf{Q}_{s-1} = \mathbf{E}_{s-1} \begin{bmatrix} \pi_{s+4} - \pi_{s+4}^* \\ \pi_{s+6} - \pi_{s+6}^* \\ \pi_{s+8} - \pi_{s+8}^* \\ \pi_{s+20} - \pi_{s+20}^* \end{bmatrix},$$

where $\mathbf{E}_{s-1}\pi_{s+4}$ is the 5-quarter-ahead forecast generated by the VAR and π^*_{s+4} is the one-year-ahead Staff Economic Projection of inflation, produced in period s, conditional on information up to $s-1$. Finally, the constant in the reduced-form interest rate equation is chosen so as to minimize the quadratic $\mathbf{Q}'_{s-1}\mathbf{W}\mathbf{Q}_{s-1}$ where $\mathbf{W}$ is a matrix that weights the different forecast horizons in the loss function.[8] We can then recover $\xi_{1,s-1}$, $\xi_{2,s-1}$, $\xi_{3,s-1}$, $\xi_{4,s-1}$ and ζ_{s-1} from $\mathbf{\Phi}_{1,s-1}$ (see Appendix A for more details) and finally recover the parameters of the rule according to

$$\overline{\pi}_s = \left\{ \frac{\left(\zeta_{s-1} - 1\right)^{-1} \xi_{1,s-1} - \overline{r}}{\left(1 - \omega_{1,s-1}\right)} \right\}, \tag{18}$$

$$\omega_{i,s-1} = \left(\zeta_{s-1} - 1\right)^{-1} \xi_{i+1,s-1} \quad i = 1, 2, 3, 4. \tag{19}$$

Thus, conditional on a choice for the steady-state real interest rate (which we calibrate to be 4 per cent, consistent with our choice of $\beta = 0.99$), the target $\overline{\pi}_s$ is just identified. This process is then repeated for all observations in the sample from 1980 up to the official adoption of an inflation target by the Bank of Canada in 1991. Thereafter, we use the actual stated target for the Staff economic projection (hereafter SEP) target.[9]

The results for the SEP approach are reported in **Figure 2**. The deviations of inflation from the estimated inflation target are very similar to those from the Kozicki and Tinsley approach, at least qualitatively. The same gap develops during the 1981-82 disinflation and the correlation between the two inflation target estimates is 0.79 over the full sample.

Table 1 provides the standard deviations and two measures of persistence for raw CPIX inflation, the two inflation gap measures and our measure of real marginal cost. In terms of the persistence measures, AR(1) refers to first-order autocorrelation coefficient and ρ refers to the largest estimated root in the series.

[8] We give a weight of one to forecast errors at all horizons except 20 quarters, which has a weight of 5. This reflects the idea that longer horizon forecasts should reveal more about the Bank's underlying inflation target.

[9] A potential issue arises as to whether the target identified here can be interpretted as agents' perceived target, as in the case of the MEP approach, given that the Staff projection data is not available to the public. To investigate this issue, we considered applying the signal extraction approach advocated by Erceg and Levin (2003), whereby agents must infer the target based on interest rate changes. Apart from making the inflation gap slightly more persistent, this modification does not change the results presented in the next section. Also, given the fact that inflation falls faster than the SEP target in the early 1980s disinflation, we believe that this variable is also interprettable as a perceived target.

First, we see that the two gap measures are less volatile and less persistent than raw inflation from 1980 to 1992, as we would expect since the low-frequency component of inflation has, in principal, been removed. Second, we note that real marginal cost is more than twice as volatile than either inflation gap, suggesting an important role will be played by the assumption of firm-specific capital in producing a reasonable value for θ.

Finally, we see that for the subsample 1993Q1-2004Q1, the volatility and persistence of the two gap series decline relative to the full sample, whereas only the volatility of real marginal cost falls (the AR(1) coefficient falls modestly from 0.86 to 0.78). Thus, while the coincident decline in volatilities is reassuring, the fact that inflation is now essentially white noise, yet real marginal cost remains quite persistent represents an outstanding issue and a useful area for future research.

Table 1: Summary Statistics for Main Variables of Interest

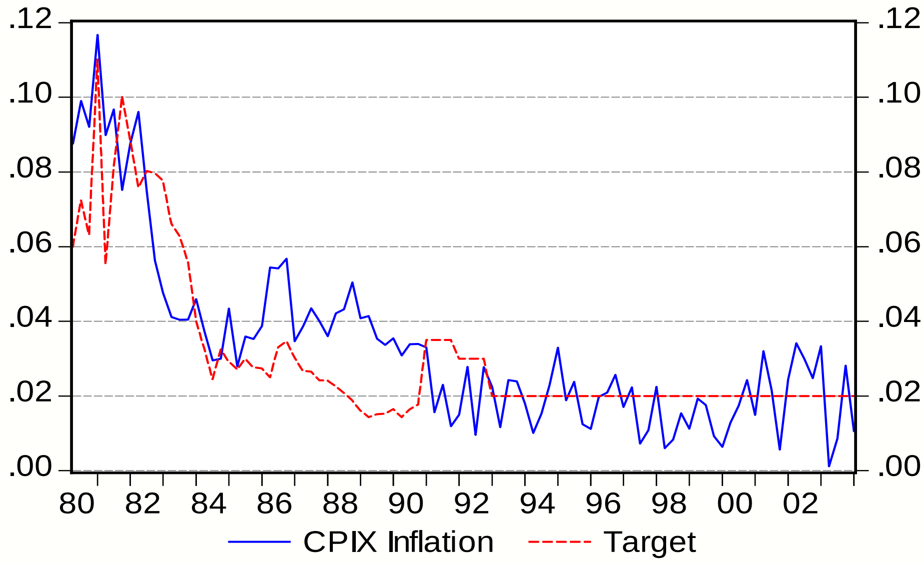
Variable	1980Q1-2004Q1			1993Q1-2004Q1		
	Std. Dev.	Persistence		Std. Dev.	Persistence	
	p.p.	ρ	AR(1)	p.p.	ρ	AR(1)
Raw CPIX	2.4	0.93*	0.87*	0.8	0.14	0.14
MEP Gap	1.3	0.69*	0.45*	0.9	0.02	0.02
SEP Gap	1.5	0.63*	0.63*	0.8	0.14	0.14
Marginal Cost	3.0	0.79*	0.86*	1.7	0.92*	0.78*

4 Estimation Method

We use a simulated method of moments (SMM) approach, similar to that developed in Smith (1993) and Gouriéroux, Monfort and Renault (1993) to estimate θ and ϕ from equation (11).[10] Generally speaking, SMM provides a method of comparing the key properties admitted from a structural model to those from the data. The data-based moments are generated from an approximating statistical model that should fit the data reasonably well but need not necessarily nest the structural model. It is noteworthy that SMM using an unconstrained VAR as the approximating model has a number of advantages. First, the inflation equation within the VAR provides an useful

[10] Our application differs slightly from that of Smith (1993) in that our model is linearized prior to estimation and there are no unobserved variables. Therefore, there is no need to generate artificial data in order to compute the model's reduced-form VAR representation.

Figure 2: SEP-Based Inflation Target



and natural metric for the degree of inflation persistence that should be captured by the structural model. Second, an unconstrained VAR does not require controversial identifying assumptions. Third, the approach allows us to match all the sample autocorrelations and cross-correlations rather than a limited set of data moments.

For the current exercise, we follow Coenen and Levin (2004) and use an unconstrained VAR in the inflation gap and our measure of marginal cost as the approximating statistical model. In effect, the method estimates the parameters of the structural model by matching its reduced-form (constrained) VAR representation as closely as possible to its unconstrained data-based counterpart. More specifically, we begin by estimating a bivariate VAR(p) from 1980 to 2004 by ordinary least squares, which we will refer to as the "auxiliary model", and then proceed to construct the vector Γ, which contains the estimated parameters of the inflation equation. Next, for a given parameterization, we combine the structural inflation equation (given by equation (11)) with the VAR equation for real marginal cost and then solve the resulting system, which we refer to as the "structural model", using a QZ decomposition (as advocated by Sims (2001)). This resulting system is a restricted VAR(p). We again extract the parameters from the reduced-form inflation equation of this system and form the vector $\Gamma(\gamma, \phi)$. Finally, the estimates of γ and ϕ from equation (11) are chosen to solve

$$\min_{\{\gamma,\phi\}} \quad (\mathbf{\Gamma} - \mathbf{\Gamma}(\gamma, \phi))' \mathbf{W} (\mathbf{\Gamma} - \mathbf{\Gamma}(\gamma, \phi)). \tag{20}$$

Then, conditional on the estimate of ϕ and our assumptions about the parameters that determine η, we then can recover θ.

In terms of determining the lag length of the auxiliary VAR, we have two options. The first is to restrict the lag length of the auxiliary model to be the same as that of the structural model's reduced-form representation, which in the case of the Calvo model with indexation is one lag. The second option is to base the lag length of the auxiliary model on some data-based criterion, such as the Akaike information criterion. For the purpose of estimation, we use a VAR(1) as our auxiliary model and for hypothesis testing, we compare it to a VAR(1) and VAR(p) where p is data determined.[11] It is worth noting that, given this strategy, the choice of weighting matrix, $\mathbf{W}$, in equation (20) is inconsequential since the model is just-identified.

5 Empirical Results

5.1 Parameter Estimates

In this section we discuss the ability of the NKPC with dynamic indexation to match important features of Canadian inflation data. Before proceeding to the estimation results, however, we mention the calibration of some model parameters (see **Table 2**). The discount rate, β, is set to 0.99 implying an annual real interest rate of 4 per cent. Following Gagnon and Khan (2005) the elasticity of substitution amongst the factors of production, σ, is set equal to 0.5 and, ϵ, the demand elasticity is calibrated to 11. The latter is consistent with results obtained by Bergin and Feenstra (2000) and implies a steady-state mark-up of 10 per cent. The labour adjustment cost parameter, χ, is 6.0, a value consistent with empirical models of labour demand for the United States (see, for instance, Nickell (1986), Meese (1980) and Sargent (1978)).[12] The share parameters (s_L and s_K) are calibrated to their historical averages. Finally, given our assumptions regarding σ, ϵ and

[11] Using a VAR(2) as the auxilary model generates an unstable model in the sense that the Blanchard-Khan condition for stability is not satisfied. This stems from the fact that marginal cost is positively related to inflation with the VAR(2) specification.

[12] Amano and Wirjanto's (1997) estimates for Canada implicitly suggest a somewhat lower value for χ, whereas the current value for χ used in TOTEM, the Bank of Canada's new projection and policy-analysis model, is higher. On balance, we feel that our choice of

s_L, the degree of real rigidity stemming from the assumption of firm-specific capital, η, is equal to 0.045. In other words, inflation in our model is more than *20 times* less sensitive to movements in marginal cost than a model that assumes a rental market for capital. This value, while implicitly calibrated, is consistent with those values estimated Coenen and Levin (2004), who use German data.

The SMM estimation results for the two measures of inflation (MEP and SEP inflation gaps) are presented in **Table 2**. The estimates of θ imply that firms, on average, re-optimize their price about once every eight months, a number well in line with survey evidence for Canada (see Amirault et al. 2005). Furthermore, the estimated duration is robust to the choice of the methodology for calculating the historical target. Under the MEP (SEP) methodology, we obtain a point estimate for the duration between re-optimizations of 2.8 (2.6) quarters, with a 90 per cent confidence interval of two to four quarters. A question that may arise from these results is: How does the NKPC model admit aggregate inflation that is moderately inertial despite the fact that firms change prices frequently? The answer lies in the result that when firms do change price they do so by only a "small" amount. This dampened price response is owning to the fact that under the firm-specific capital assumption each firm's short-run marginal cost is increasing in its own output. To better understand this result consider a firm contemplating a price increase. The firm understands that a higher price implies less demand and less output. A lower level of output reduces marginal cost and, thus, induces the firm to post a lower price. Thus, the dependence of marginal cost on firm-level output reduces the firm's incentive to raise it price. This dampening influence explains why aggregate inflation responds less to a given aggregate cost shock even though firms reoptimize their price very frequently.

The degree of dynamic indexation is estimated to be a very moderate 0.37, regardless of the measure of the inflation gap. The 5^{th} and 95^{th} percentiles for the point estimate (using the MEP-based gap) are 0.1 and 0.65, thus we can rule out both zero indexation and full indexation. The values for the forward- and backward-looking components are consistent with the results reported in Gali and Gertler (1999) and Gali, Gertler and Lopez-Salido (2001), and show that, even if the canonical NKPC is rejected in favour of an equation allowing for additional inertia coming from lagged inflation, the weight on the forward-looking component is quantitatively more

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6 as a value is reasonable. Furture work, however, should look at estimating this parameter directly for Canada since it influences importantly our measure of marginal cost.

relevant (0.72 versus 0.27 on lagged inflation according to our estimates), an especially important point from the perspective of a monetary authority.

Turning to the overall fit of the model, we see (**Table 3**) that the structural model explains a slightly higher (lower) proportion of the overall variation in the SEP (MEP) inflation gap relative to the unrestricted VAR(2) inflation equation.[13] This would suggest that nothing is lost by working with the structural model (with the SEP gap), at least in terms of in-sample fit. Given this result, it is not surprising that the restrictions imposed by the Calvo model with indexation are not rejected by the data using the SEP gap. For the MEP gap, the difference in $\overline{R}^2$ is just 0.02, 0.36 versus 0.38. Nevertheless, this difference is sufficiently large to produce a probability value of 0.051 using the LR test under the null that the restrictions imposed by the structural model are true.

Comparisons with the VAR(1) can be easily summarized once we recognize that the structural model does not impose any binding restrictions relative to a VAR(1). With the indexation parameter free to vary on the $[0, 1]$ interval and ϕ only restricted to be positive, the reduced form of the estimated structural model corresponds exactly to that of the auxiliary model.

5.1.1 Comparisons to the Standard Model

In this section we investigate the effects of relaxing several assumptions implicit in our preferred specification. More specifically, we begin by estimating the canonical NKPC, the Calvo model without indexation and firm-specific capital (see column 1 of **Table 4**). Here we see that, consistent with our priors and past research using Canadian GDP deflator inflation, the canonical model fails to adequately capture the dynamics of inflation along several margins. First, we can easily reject the null hypothesis of no serial correlation in the residuals using the Q-statistic. Second, the model produces a $\overline{R}^2$ of less than 0.1, compared to 0.83 for the unrestricted VAR(2) equation for inflation. Not surprisingly, we easily reject the restrictions imposed by the structural model using a LR test. Finally, the model suggests that firms reoptimize prices on average about once every two years, which seems unreasonably long.

When partial indexation is added to this basic model, the overall fit improves significantly, but we continue to reject the restrictions imposed by the model. Specifically, the unrestricted model prefers two lags of inflation

[13] The restricted model is able to explain a higher proportion because our measure of fit is the adjusted R-square, which adjusts for degrees of freedom.

whereas the indexation model admits just one. Furthermore, it implies an average duration between price reoptimizations of *4 years*. Thus, it appears that neither of these two models is consistent with raw CPIX inflation. Next, we attempt to model the SEP-based inflation gap, allowing for partial indexation but continue to maintain the assumption of a rental market for capital ($\eta = 1$). In this case, the model matches the preferred model in every respect except that it predicts that firms reoptimize prices, on average, about once every 11 quarters.

Finally, we estimate the preferred specification (indexation with firm-specific capital) but replace our measure of marginal cost with labour's share of final good income, which is equivalent to setting adjustment costs on employment to zero and the elasticity of substitution between production inputs to unity; that is, $\chi = 0$ and $\sigma = 1$. Interestingly, we see that in this instance the optimization algorithm drives $\phi = 0$, implying an average contract duration that is infinite. This stems from the fact that this measure of marginal cost is unrelated to inflation. Owing to the inclusion of indexation, the model succeeds in explaining about 38 per cent of the historical movements in the inflation gap, compared to 54 per cent for the unrestricted model that uses the preferred marginal cost measure ($\chi = 6$ and $\sigma = 0.5$).[14] Finally, labour's share is not significant in the inflation equation of the unrestricted auxiliary model.

5.2 Moment Matching

As discussed earlier, SMM proceeds by matching the reduced-form of the structural model to that of an unrestricted VAR. A natural starting point for assessing the moment matching ability of the NKPC is a comparison of its implied vector autocorrelations with the sample autocorrelations from the observed data. **Figure 4** compares the cross correlations of the estimated model to that of the auxiliary model (bivariate VAR(1) in the inflation gap and real marginal cost). From the figure it is apparent that when the data are assumed to be generated by a VAR(1), the structural model imposes no binding restrictions on the reduced form, and, consequently, the model is able to reproduce the VAR dynamics exactly. The more interesting case arises when the structural model is compared to a VAR(2) (see **Figure 5**), where the choice of two lags is data determined (although the auxiliary model used for estimation remains a VAR(1)). Again, the NKPC does very well at matching the dynamic cross correlations found in data. The

[14] We do not conduct a LR test in this instance since the models are non-nested.

autocorrelation function for inflation and the cross correlations with real marginal cost implied by the structural model, for instance, all lie well within the 95 per cent confidence intervals.

5.3 Forecasting Comparison

Another method to examine the ability of the estimated NKPC model to reproduce key features of Canadian inflation data is to compare its forecasting ability with that from reasonable alternative models. For the latter, we employ two often-used models of inflation: A simple AR(p) model, where p is data determined; and (ii) a traditional output gap based Phillips curve. Stock and Watson (1999) find the traditional Phillips curve, interpreted broadly as relations between real economic activity and inflation, produces reliable and accurate short-run forecasts of inflation across a wide range of inflation forecasting models, at least for U.S. price inflation. The traditional Phillips curve, therefore, appears to be a reasonable metric for comparison.[15] Moreover, in the forecasting exercises we calculate the output gap using a two-sided filter. To the extent the two-sided filter uses future information, the forecasting results are biased in favour of the traditional Phillips curve equation.

We start by estimating each model on data up to 1984Q4 and then calculate a one-step ahead forecast. Another period of data is added, each equation is re-estimated and new forecasts are generated. This process is repeated until the end of our data set. To evaluate the forecasting performance of each model, we compare mean square errors (MSEs) from the alternative specifications to those generated by the NKPC model. To this end, we report Diebold and Mariano (1995) test statistics in **Table 5**. The Diebold and Mariano (DM) approach tests the hypothesis that the MSEs are equal versus the alternative that one model performs better than another in out-of-sample forecasting.[16]

The evidence suggests that the NKPC with partial dynamic indexation

[15] The Phillips curve used here is given by $\pi_t = \alpha_1\pi_{t-1} + \alpha_2\pi_{t-2} + \alpha_3\widetilde{y}_{t-1} + u_t$. The AR(2) model sets $\alpha_3 = 0$.

[16] As a check on the robustness of the results generated using the DM test, we also calculate the test statistic proposed by Granger and Newbold (1977). This test is useful in the cases where the forecast errors from one model are correlated with those from another (since this would render the usual variance ratio or F test inappropriate). The Granger and Newbold test, unfortunately, is valid only when the forecasts are unbiased and the forecast errors are uncorrelated. These results are excluded from the table as they are essentially the same as the DM results.

has greater predictive power than either of the two competing models.[17] In all experiments, we find the estimated NKPC model to perform significantly better than the AR(2) or traditional Phillips curve models. Specifically, the null that the MSE of both models is the same is rejected at the one per cent in favour of the alternative that the MSE from the structural model is smaller.

6 Concluding Remarks

In this paper, we examined the ability of the New Keynesian Phillips Curve with partial dynamic price indexation to capture key features of Canadian inflation data. Our study, however, differs from earlier research along three important dimensions. In particular, we relax three assumptions often made in the NKPC literature, *viz.*, (i) constant (and observable and credible) inflation target; (ii) labour's share of income as a measure of marginal cost; and (iii) rental market for capital. Overall, we find that the NKPC with partial dynamic indexation appears capable of reproducing important moments of Canadian inflation data. Indeed, the estimated model replicates both the inflation persistence found in macroeconomic data in addition to durations between price reoptimizations that we view as very reasonable. The NKPC also replicates important vector autocorrelations found in the data; in all cases the model and data vector autocorrelations are statistically indistinguishable. Finally, a forecasting comparison exercise indicates that the estimated NKPC outperforms statistically other often used inflation forecasting models such as an AR(2) and traditional Phillips curve equations. We interpret these results as additional evidence that models need not sacrifice data congruence, measured in terms of goodness of fit and forecasting precision, in order to provide more a structural interpretation of economic events. We view this as good news for micro-founded models of pricing behaviour such as the Calvo (1983) model for Canada.

Going forward, it would be interesting to further explore the reasons behind the apparent decline in the persistence of both our inflation gap measures. As discussed in the text, it is difficult to understand why such a decline in persistence should not be accompanied by a corresponding decline in the persistence of real marginal cost. This would seem to point to some form of misspecification to either our marginal cost series or our inflation gap variables. It would also be interesting to explore whether the SEP approach

[17] The finite-sample adjustment to the DM test statistic proposed by Harvey, Leybourne and Newbold (1997) does not change the conclusions.

to identifying the historical inflation objective of the central bank discussed in this paper could also be usefully applied to other countries.

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Figure 3: MEP-Based Inflation Gap and Normalized Marginal Cost

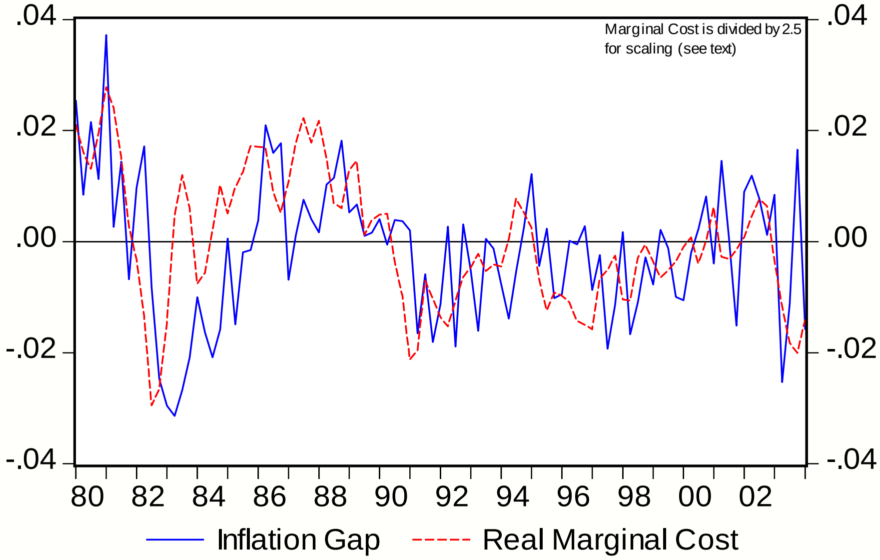


Table 2: Calibrated Parameters

Parameter	Value
σ	0.5
β	0.99
ϵ	11
χ	6.0
s_L	0.46
s_K	0.37
Functions of Calibrated Parameters	Value
μ	1.1
η	0.045
Θ	0.84
Λ	0.66

Table 3: Estimation Results - Preferred Model

Variable	SMM (1980Q1-2004Q1)			
	MEP Inf. Gap		SEP Inf. Gap	
NKPC	VAR(1)	VAR(2)	VAR(1)	VAR(2)
γ	0.37 [0.1 0.65]		0.37 [0.23 0.7]	
Av. Duration	**2.8** quarters [2.0 4.0]		**2.6** quarters [1.8 3.5]	
$\overline{R}^2$	0.36	0.36	0.54	0.54
$LB\ Q-stat$	2.18	2.18	1.99	1.99
VAR(2)				
$\overline{R}^2$	0.35	0.38	0.53	0.52
$LB\ Q-stat$	2.18	2.04	1.99	2.00
H_0: $NKPC = VAR$	**1.00**	**0.051**	**1.00**	**0.3**

Table 4: Estimation Results - Variations on the Preferred Model

Variable	Raw CPIX Inflation		SEP Inf. Gap		
NKPC	$\eta = 1, \gamma = 0$	$\eta = 1$	$\eta = 1$	$\eta < 1$	$\widehat{\lambda}_t = \widehat{s}_t$
γ	0	0.97	0.37	0.37	0.53
Av. Duration	8.9 quar.	16.1	10.8	2.6	∞
$\overline{R}^2$	0.06	0.80	0.54	0.54	0.38
$LB\ Q-stat$	0.00	0.00	0.4	0.4	0.28
VAR(2)					
$\overline{R}^2$	0.83	0.83	0.52	0.52	0.52
$NKPC = VAR$	**0.00**	**0.00**	0.3	0.3	**0.00**

Figure 4: Cross Correlations: VAR(1) with SEP-Based Inf. Gap

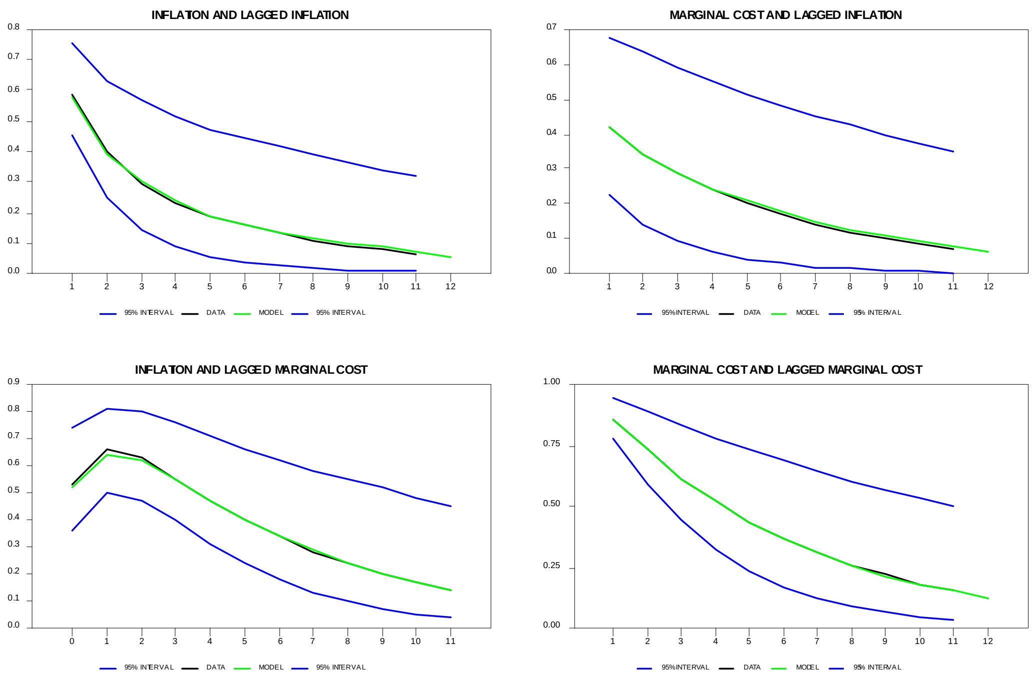
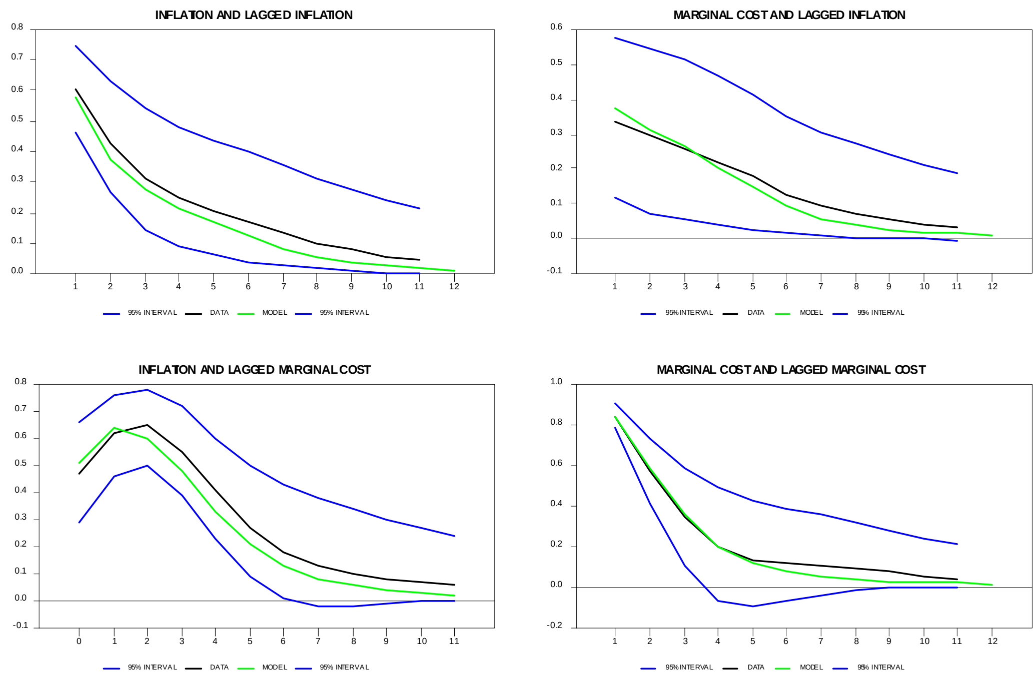


Table 5: Forecast Results (1985Q1 - 2004Q1)

Model	Forecast RMSE Tests	
	MEP Inf. Gap	SEP Inf. Gap
NKPC	**0.23**	**0.21**
YGAP Phil. Curve	0.26	0.25
AR(2)	0.25	0.24
Diebold-Mariano Test	Prob. Value under null of equal RMSE (σ)	
$\sigma_{NKPC} < \sigma_{YGAP}$	0.00	0.00
$\sigma_{NKPC} > \sigma_{YGAP}$	1.00	1.00
$\sigma_{NKPC} < \sigma_{AR(2)}$	0.01	0.02
$\sigma_{NKPC} > \sigma_{AR(2)}$	0.99	0.98

Figure 5: Cross Correlations: VAR(2) with SEP-Based Inf. Gap



Appendix A

If the non-structural component follows a VAR(p)

$$\begin{bmatrix} c_t \\ \pi_t \\ \widetilde{y}_t \\ \Delta z_t \end{bmatrix} = \sum_{i=1}^{p} \mathbf{A}_i \begin{bmatrix} c_{t-i} \\ \pi_{t-i} \\ \widetilde{y}_{t-i} \\ \Delta z_{t-i} \end{bmatrix} + \mathbf{u}_t$$

where c is a simply a timeseries one ones intended to capture the constant. The policy rule is given by

$$R_t = \zeta_t R_{t-1} + \mathbf{E}_{t-1} \left(1 - \zeta_t\right) \left(\overline{r} + \pi_t + \omega_{1,t} \left(\pi_t - \overline{\pi}_t\right) + \omega_{2,t} \widetilde{y}_t + \omega_{3,t} \Delta z_t\right) + \varepsilon_t$$

so in structural form we have[18]

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ \xi_1 & \xi_2 & \xi_3 & \xi_4 & 1 \end{bmatrix} \begin{bmatrix} c_t \\ \pi_t \\ \widetilde{y}_t \\ \Delta z_t \\ R_t \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ \alpha_{21} & \alpha_{22} & \alpha_{23} & \alpha_{24} & \alpha_{25} \\ \alpha_{31} & \alpha_{32} & \alpha_{33} & \alpha_{34} & \alpha_{35} \\ \alpha_{41} & \alpha_{42} & \alpha_{43} & \alpha_{44} & \alpha_{45} \\ 0 & 0 & 0 & 0 & \lambda \end{bmatrix} \begin{bmatrix} c_{t-1} \\ \pi_{t-1} \\ \widetilde{y}_{t-1} \\ \Delta z_{t-1} \\ R_{t-1} \end{bmatrix} + ... + \mathbf{A}_p \mathbf{X}_{t-p} + \mathbf{u}_t$$

or

$$\mathbf{A}_0 \mathbf{X}_t = \mathbf{A}_1 \mathbf{X}_{t-1} + ... + \mathbf{A}_p \mathbf{X}_{t-p} + \mathbf{u}_t$$

with

$$\begin{aligned} \xi_1 &= (\lambda - 1)\left(\overline{r} - \omega_1 \overline{\pi}_t\right) \\ \xi_2 &= (\lambda - 1)\left(1 + \omega_1\right) \\ \xi_3 &= (\lambda - 1)\,\omega_2 \\ \xi_4 &= (\lambda - 1)\,\omega_3 \end{aligned}$$

Hence, the coefficient matrix at lag one of the reduced-form VAR that we estimate, is related to the structural model as

[18] The t subscript has been supressed on coefficients. In practice they vary through time, however, given that the reduced-form VAR is estimated recursively.

$$\Phi_1 = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ \alpha_{21} & \alpha_{22} & \alpha_{23} & \alpha_{24} & \alpha_{25} \\ \alpha_{31} & \alpha_{32} & \alpha_{33} & \alpha_{34} & \alpha_{35} \\ \alpha_{41} & \alpha_{42} & \alpha_{43} & \alpha_{44} & \alpha_{45} \\ \eta_1 & \eta_2 & \eta_3 & \eta_4 & \eta_5 \end{bmatrix}$$

$$= \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ \xi_1 & \xi_2 & \xi_3 & \xi_4 & 1 \end{bmatrix}^{-1} \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ \alpha_{21} & \alpha_{22} & \alpha_{23} & \alpha_{24} & \alpha_{25} \\ \alpha_{31} & \alpha_{32} & \alpha_{33} & \alpha_{34} & \alpha_{35} \\ \alpha_{41} & \alpha_{42} & \alpha_{43} & \alpha_{44} & \alpha_{45} \\ 0 & 0 & 0 & 0 & \lambda \end{bmatrix}$$

with

$$\begin{aligned} \eta_1 &= -\xi_1 - \xi_2\alpha_{21} - \xi_3\alpha_{31} - \xi_4\alpha_{41} \\ \eta_2 &= -\xi_2\alpha_{22} - \xi_3\alpha_{32} - \xi_4\alpha_{42} \\ \eta_3 &= -\xi_2\alpha_{23} - \xi_3\alpha_{33} - \xi_4\alpha_{43} \\ \eta_4 &= -\xi_2\alpha_{24} - \xi_3\alpha_{34} - \xi_4\alpha_{44} \\ \eta_5 &= \lambda - \xi_2\alpha_{25} - \xi_3\alpha_{35} - \xi_4\alpha_{45} \end{aligned}$$

In matrix form, this system of equations may be expressed as

$$\begin{bmatrix} 1 & \alpha_{21} & \alpha_{31} & \alpha_{41} & 0 \\ 0 & \alpha_{22} & \alpha_{32} & \alpha_{42} & 0 \\ 0 & \alpha_{23} & \alpha_{33} & \alpha_{43} & 0 \\ 0 & \alpha_{24} & \alpha_{34} & \alpha_{44} & 0 \\ 0 & \alpha_{25} & \alpha_{35} & \alpha_{45} & -1 \end{bmatrix} \begin{bmatrix} -\xi_1 \\ -\xi_2 \\ -\xi_3 \\ -\xi_4 \\ -\lambda \end{bmatrix} = \begin{bmatrix} \eta_1 \\ \eta_2 \\ \eta_3 \\ \eta_4 \\ \eta_5 \end{bmatrix}$$

so the solution for the structural parameters in terms of the reduced-form VAR parameter matrix (at lag one) is

$$\begin{bmatrix} \xi_1 \\ \xi_2 \\ \xi_3 \\ \xi_4 \\ \lambda \end{bmatrix} = \begin{bmatrix} 1 & \alpha_{21} & \alpha_{31} & \alpha_{41} & 0 \\ 0 & \alpha_{22} & \alpha_{32} & \alpha_{42} & 0 \\ 0 & \alpha_{23} & \alpha_{33} & \alpha_{43} & 0 \\ 0 & \alpha_{24} & \alpha_{34} & \alpha_{44} & 0 \\ 0 & \alpha_{25} & \alpha_{35} & \alpha_{45} & -1 \end{bmatrix}^{-1} \begin{bmatrix} -\eta_1 \\ -\eta_2 \\ -\eta_3 \\ -\eta_4 \\ -\eta_5 \end{bmatrix}$$

and the parameters of the rule are given by

$$
\begin{aligned}
\left\{\frac{(\lambda-1)^{-1}\,\xi_1-\overline{r}}{(1-\omega_1)}\right\} &= \overline{\pi}_t \\
\left\{(\lambda-1)^{-1}\,\xi_2\right\} &= \omega_1 \\
\left\{(\lambda-1)^{-1}\,\xi_3\right\} &= \omega_2 \\
\left\{(\lambda-1)^{-1}\,\xi_4\right\} &= \omega_3.
\end{aligned}
$$