Are Inflation-Targeting Regimes Credible?
Econometric evidence[1]

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Abstract

A central bank that achieves and *maintains* its objective of a low (mean) and stable (variance) inflation rate, and does not attempt to exploit the trade-off between real output (relative to trend) and inflation is said to be *credible*. Maintained low and stable inflation reduces the variability of aggregate demand shifts. When aggregate demand shocks dominate the changes in real output and inflation, most of the increase in demand will result in higher real output than in inflation. This favourable trade-off is due to credibility and explains why money supplies and real output have been growing at much faster rates than prices in low and stable inflation countries. Time-series and pooled time-series and cross-sectional structural models are estimated and it is found that these hypotheses cannot be rejected using data from Australia, New Zealand, Sweden. However, the cases of Canada and the United Kingdom are less obvious.

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[2] The views expressed in this paper are mine and do not necessarily reflect those of the Reserve Bank of New Zealand.

1. Introduction

There has been an increasing interest in inflation targeting as a policy regime (e.g., Bernanke and Mishkin, 1997). The number of countries pursuing such objective has been increasing since New Zealand started in 1989. Examining the (macroeconomic) credibility effects of the existing inflation-targeting regimes may help policymakers, who have been thinking about adopting such a regime, make an informed decision.

The time series data for a few inflation-targeting regimes are available now, which motivates an econometric examination of the credibility of the policy regime. In this paper I test the hypothesis that the inflation-targeting regimes of Australia, Canada, New Zealand, Sweden and the United Kingdom are credible.[3]

There are many different definitions of credibility such as those found in Persson (1988) who provides a good and broad survey of the literature. Blinder (1999) defines credibility as "words matching deeds". Also, Svensson (1999) who argues that a central bank is credible when private inflation expectations are consistent with the central bank's goal: "for a central bank with an explicit target, credibility occurs when private inflation expectations coincide with the inflation target. Cukierman and Meltzer (1986) define credibility as the speed with which the public recognises changes in the objectives of the central bank.[4] And Faust and Svensson (1999) argue that a low-credibility central bank is one that conducts a more expansionary policy than a high-credibility bank, in the sense that its policy causes higher inflation—even though its policy induces lower inflation and unemployment than expected.

I will use a simple and a familiar definition of credibility. I define credible central banks as those that do not exploit the trade off between real output and inflation. A credible central bank stabilises aggregate demand *shifts* by stabilising the inflation rate. *Ceteris paribus*, its expansionary monetary policy shifts the aggregate demand curve up and increases real output relative to trend, but with few inflationary consequences. Lucas (1973) shows that this kind of trade-off occurs when inflation is stationary and has low variability.

Today, we have accumulated a reasonable amount of data from several inflation-targeting experiences, which permit us to test hypotheses. The Lucas model is like the New Keynesian Ball, Mankiw and Romer (1988) sticky-price model, where the slope of the Phillips curve depends on the variance of demand in cases where demand fluctuates widely. However, persistence is present for a different reason, imperfect information. The reader should check Ball et al. acknowledgement of the similarity. Interestingly, a recent paper by Mankiw and Reis (2001) modifies the New Keynesian Phillips curve using the imperfect information assumption in Lucas (1973). It seems that the differences between the Neoclassical and the New Keynesian models are getting smaller, which is a positive development.

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[3] Data on other regimes are not readily available.

[4] The reason for low credibility is the central bank's inability to control money growth *perfectly*. They suggest, this lack of perfection is the source of the *inflation bias*, which results from a central bank attempting to boost output growth. Imperfect control over money growth raises the average rate of monetary growth above the rate required for price stability and thus decreases credibility.

Therefore, the paper is based entirely on Lucas' argument. Equilibrium output and price equations with cross-equations restrictions derived from a structural Lucas aggregate supply function, a simple aggregate demand and rational agents are estimated. The hypothesis is: credible central banks that *successfully maintain* low (mean) and stable (variance) inflation rates for a reasonably long periods of time reduce the correlation between the growth rate of the money supply and inflation. Thus, *ceteris paribus*, monetary expansion (upward shifts in aggregate demand) increases real output relative to trend more than it increases inflation. This is termed a favourable trade-off due to credibility. Evidence is obtained from time-series and pooled time-series and cross sectional data of five inflation-targeting regimes.

The hypothesis is tested using quarterly data for Australia, Canada, New Zealand, Sweden, and the United Kingdom. Two samples representing two different regimes are used. The first sample covers periods of high inflation and disinflation episodes. The second sample covers periods of inflation targeting in which inflation rates are maintained at low and stable levels.

The data examined in this paper suggest that in countries where aggregate demand shocks dominate changes in real output and inflation (Australia, New Zealand and Sweden) monetary expansions are not inflationary when the regimes are credible. In other words, when central banks do not exploit the Phillips curve, and stick to their objectives of low and stable inflation rates.

The results for Canada and the United Kingdom are less obvious. The effect of aggregate demand shifts on inflation and real output fluctuations remained *unchanged* during the period of low and stable inflation regimes. The model predicts that *if* those central banks pursued credible policies of the type described earlier, these results indicate that the stability of inflation is apparently *offset* by instability in relative prices. Instability of relative prices is not the focus of this paper (see Debelle and Lamont (1997) and Fielding and Mizen (2000) for empirical evidence from the U.S. and European cities).

Section 2 describes the data and provides graphical analysis and descriptive statistics. Section 3 discusses the properties of Lucas' structural model, estimates it and interprets the results. Section 4 is a summary.

2. Data

The New Zealand data are from the Reserve Bank of New Zealand. The Swedish data are from the Sveriges Riksbank.[5] The rest of the data used in this paper are from Datastream. The data are quarterly real and nominal production GDP and they are seasonally adjusted.

The analysis covers two periods, where each period represents a *different policy regime*. The first period covers high inflation and disinflation episodes. The second period covers inflation-targeting regimes. The exchange rate regime operating in both periods for all countries is the floating exchange rate. The samples vary in length

[5] I thank Goran Zettergren for providing the data.

across countries depending on the date each country floated its currency and the availability of the data.

2.1 Plots of the inflation rates

Figures 1a-1f plot two measures of the inflation rates namely the CPI inflation rates and the GDP deflators. Visually, the levels of the inflation rates seem to have declined substantially and remained low from 1992 onwards. The stability (variance) and the non-stationarity will also be examined.

Based on figure 1, it seems reasonable to construct the first sub-samples for high inflation and disinflation regimes. The first sub-sample for Canada, Sweden and the United Kingdom is from 1983Q1 to 1991Q4. Australia and New Zealand floated their currencies in 1983Q2 and 1985Q2 respectively, so their first sub-samples start at those dates.

The second sub-samples represent regimes of *maintained* low and stable inflation rates. For Australia, New Zealand and Canada the second sub-samples start from 1992Q1, but they end at different dates depending on the availability of the data. For Australia the sub-sample ends in 1999Q1, but for Canada and New Zealand the samples end in 1998Q3 and 1998Q1 respectively.

The United Kingdom and Sweden samples are different. The United Kingdom and Sweden were members of the European Exchange Mechanism (ERM). In September 1992, the United Kingdom abandoned the ERM and in October 1992 adopted an inflation-targeting regime. Sweden also exited from the ERM and adopted an inflation-targeting regime in 1993. During1992, both the United Kingdom Pound and the Swedish Krone suffered from massive speculative attacks. To avoid unnecessary volatility in the data, observations from 1992Q1 to 1993Q3 are thrown away. The samples are from 1993Q4 to 1999Q1.

Figures 2(a-f) plot annual inflation and nominal output growth rates. For Australia, Canada, Sweden, and the United Kingdom, nominal output grew faster than prices almost over the entire sample. New Zealand is the only country where income growth and inflation were highly correlated during the period of disinflation from 1985Q2 to 1991Q4. However, the correlation broke down in 1992 and income continued to grow at much faster rate than the price level up until 1998Q1, where inflation and nominal output growth become close.

A similar pattern is observed in the cases of Canada (2c) and the United Kingdom (2e); inflation and nominal output growth rates are converging. In Australia, and Sweden there is a pattern of divergence at the end of the sample, particularly for Sweden. This lack of correlation between inflation, and nominal output growth rates could be interpreted as evidence of the success of central banks in controlling inflation and may indicate high credibility.

Figures 3(a-f) plot the nominal and the real income growth rates. When compared with the periods of high inflation and disinflation, the wedge between them is smaller during the periods of inflation targeting in all countries. This convergence is basically the prediction of the Lucas model, which will be tested more rigorously in the remainder of this paper.

2.2 Descriptive statistics

Table 1 reports sample means and variances of the inflation rates, nominal output growth and real output growth.[6] The results indicate that the means of the inflation rates declined significantly under inflation targeting. The variances of the inflation rates, nominal output growth and real income growth have also declined significantly.

However, there are three exceptions. First, the variance of the inflation rate in Canada remained unchanged across different regimes. Though, compared with other variances, the magnitudes of the variability of the Canadian inflation rate across regimes are small. Second, the variance of real GDP growth in New Zealand remained constant across regimes. Third, the variance of nominal GDP growth in Sweden remained unchanged across regimes.

One conclusion that emerges from table 1 is that these inflation-targeting countries have achieved their announced objectives of low and stable inflation rates, and successfully, *maintained* them low and stable for a period of time to date. To test this formally, the Augmented Dickey-Fuller test is used to test for a unit root in the inflation rates from 1992 onward (This is the period of maintained stable inflation). The null hypothesis that the inflation rates have unit roots is rejected easily. It is safe to conclude that the inflation rates during the periods of inflation targeting are stationary (results are not reported but they are available upon requests).[7]

3. The model

I will briefly explain the Lucas (1973) supply function, which will be combined with a simple aggregate demand to derive equilibrium equations that I will fit to the data. I will also explain why this model is appropriate to fit the data. The Lucas (1973) model represents a structural analysis of the real output-inflation trade-off within a natural rate paradigm (Phelps, 1967) and Friedman (1968).

The model is structural in the sense that the Lucas aggregate supply curve (AS) is derived from first principles and most economists would agree about it in the sense that it assumes long-run neutrality.[8] The other supply curve that is widely used in the literature is the Calvo supply curve due to (Calvo, 1983), Rotemberg (1982) and Taylor (1980), which is derived from staggered contracts type of models. Unlike the Lucas supply function, these supply curves do not possess the Natural Rate Hypothesis.

In the Lucas model, output is completely determined by the suppliers of labour and output, which is a standard neo-classical assumption. Let P_t, y_t, x_t be the natural

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[6] The inflation rate is defined as $(\ln P_t - \ln P_{t-4})*100$, where P_t is the CPI. Output growth rates are computed in the same fashion, where nominal output is nominal GDP and real output is real GDP.

[7] The data required different lag structures. The lags are set to between 1 and 2 lags because the sample is relatively small, but the residuals of the ADF regressions are white noise.

[8] See Lucas and Rapping (1969) for details about the aggregate supply curve.

logarithms of the price level, real output and nominal output respectively. There exist a large number of geographically separated markets, where goods are traded in all markets. The demands for the goods vary from one market to another. The markets are indexed by z . The quantity of output supplied in each market is the product of a normal or a secular component, which approximate potential output y_{pt} and a cyclical component, $y_{ct}(z)$, which also varies from one market to another. Thus, we have $y_t(z) = y_{pt} + y_{ct}(z)$. Lucas models the secular component as $y_{pt} = \alpha + \beta t$, but it could be modelled differently and in this paper we use the HP filter for simplicity. The cyclical component is given by $y_{ct}(z) = \gamma[P_t(z) - E_t P_t] + \phi y_{c,t-1}(z)$. The actual price level in market z is $P_t(z)$ and $E_t P_t$ is the average general (economy-wide) price level conditioned on information available in market z at time t .

The information available to suppliers at time t is not sufficient to determine the current general price level exactly. Thus, it is unobservable. Suppliers in a typical market have *imperfect information* about the general price level. It should be emphasised that this is the main source of rigidity in the model as opposed to staggered contracts or menu costs. Information though is sufficient to determine the distribution of the general price level P_t , which is common to all traders in all markets. The central assumption in the Lucas model is that this distribution is known and correct with a mean $\overline{P}_t$ and a variance σ^2 .

It is also assumed that the percentage deviation of the price in market z from the general price level is denoted z , where z is distributed normal with mean zero and variance τ^2 . Thus, Lucas writes $P_t(z) = P_t + z$. The estimation of the unobserved price level is based on information about $P_t(z)$ and $\overline{P}_t$. The mean of this normal distribution is given by the linear combination $(1-\theta)P_t(z) + \theta\overline{P}_t$, where

$\theta = \dfrac{\tau^2}{\sigma^2 + \tau^2}$ and a variance $\theta\sigma^2$.

Combining all of the above results in the supply function $y_t(z) = y_{pt} + \theta\gamma[P_t(z) - \overline{P}_t] + \phi y_{ct-1}(z)$. And averaging over markets gives the Lucas aggregate supply function $y_t = y_{pt} + \theta\gamma[P_t - \overline{P}_t] + \phi[y_{t-1} - y_{p,t-1}]$. The parameter γ captures the responsiveness of the cyclical output component to changes in *relative prices*. The cyclical component of real output $y_{ct} = y_t - y_{pt}$, varies with changes in *relative prices* $P_t - \overline{P}_t$.

The fact that θ depends on τ^2 and σ^2 implies that the suppliers' main task is to distinguish whether demand shifts constitute an increase in aggregate demand or an increase in the demand in their specific market. This process is known as the signal extraction problem. The central bank can surprise suppliers by expansionary monetary policy, which shifts the aggregate demand curve. Typical suppliers who observe the actual price level to be higher than their expected price may increase their production in the short run and the central bank would achieve its goal of higher real output. They will realise that they have confused aggregate demand shifts with local demand shifts. When they realise this they cut down production and output returns to equilibrium. The reverse is also true when the central bank pursues a surprisingly tight monetary policy. The model, however, allows this to happen for one period only. The assumption is that rational suppliers cannot be fooled twice.

The aggregate demand is kept simple, but could be derived from first principles too and dependants on expectations like in the New Keynesian model or like in McCallum and Nelson (1999) and Kerr and king (1996). The model assumes that nominal output is determined on the aggregate demand side of the economy (i.e. the IS-LM model), with the division into real output and the price level. Algebraically, the AD curve is given by $x_t = y_t + P_t$. The AD curve is assumed to be a unit-elastic, which means that the level of nominal output can be treated as an exogenous variable. This is assumption is testable and I will tests later in this paper, but it is probably unrealistic and must be treated in some way or another.

Given the AS and AD curves, the model is solved for the equilibrium values of real output and price levels, which links supply parameters to parameters governing the stochastic nature of demand *shifts*. In logs, the two equations are given by:

$$y_t = -\frac{\theta\gamma\delta}{1+\theta\gamma} + \phi\beta + \frac{\theta\gamma}{1+\theta\gamma}\Delta x_t + \phi y_{t-1} + (1-\phi)\,y_{p,t} \qquad (1)$$

$$P_t = \frac{\theta\gamma\delta}{1+\theta\gamma} - \phi\beta + \frac{1}{1+\theta\gamma}x_t + \frac{\theta\gamma}{1+\theta\gamma}x_{t-1} - \phi y_{t-1} - (1-\phi)\,y_{p,t} \qquad (2)$$

Equation (1) describes real output as a positive function of nominal output growth Δx_t, lagged real output y_{t-1} and potential output $y_{p,t}$. The parameters and their signs represent theoretical restrictions.

Equation (2) describes the log of the price level P_t as a positive function of nominal output x_t and its lagged value; a decreasing function of lagged real output y_{t-1}, and potential output $y_{p,t}$.[9] Thus, when the AS curve shifts to the right real output increases and the price level falls.

The slope of the AS curve varies with the fraction θ of total individual price variance, $\tau^2 + \sigma^2$, which is due to *relative price* variations. An increase in growth rate of the money supply shifts the AD curve up and alters relative prices. For example, when τ^2 is relatively small so that the individual price changes are virtually certain to reflect general price changes, the supply curve is nearly vertical. On the other hand, if the general price level is stable, i.e. σ^2 is small, then the slope of the aggregate supply curve approaches the value of γ.

Note that the predictions of the Lucas model that the slope of the aggregate supply curve (Phillips curve) depends on the variance of demand in cases where demand fluctuates widely is *not* different from those derived from sticky price models later on

[9] Nominal GDP may not be a very good proxy for demand because macro data have serious measurements' problems and limited amount of information.

(Ball, Mankiw and Romer, 1988). The interpretations are different and the reasons are different. The reader should check Ball et al. acknowledgement of the similarity.

In terms of deviations of output from potential (output gap) and inflation, equation (1) and (2) become:

$$y_{ct} = -\delta\eta + \eta\,\Delta x_t + \phi\, y_{c,t-1} + u_{1t} \tag{3}$$

$$\Delta P_t = -\beta + (1-\eta)\,\Delta\, x_t + \eta\,\Delta x_{t-1} - \phi\,\Delta\, y_{c,t-1} + u_{2t} \tag{4}$$

Full derivation of (3) and (4) is found in the appendix. Recall that β in (4) is the trend of real output. The parameter η ($\eta = \dfrac{\theta\gamma}{1+\theta\gamma}$) is the parameter that we use for testing our hypothesis about the output-inflation trade-off and credibility. The conditional variance of P_t will be a constant equal to:

$$\sigma^2 = \frac{1}{(1+\gamma\theta)^2\sigma_x^2}\,. \tag{5}$$

It is important to recognise how the model asserts the existence of the natural rate hypothesis. The parameter δ is the average rate of demand expansion with a negative sign. It means that changes in the average rate of nominal output growth have no effect on average real output in the long run. For example, in the long run, $y_{c,t}$ is zero, so $\delta = \Delta x_t$. The natural rate paradigm implies that there exists no unique inflation rate such that the central bank can choose to keep real output higher than its normal level (i.e. potential) *permanently*.[10]

Combining $\eta = \dfrac{\theta\gamma}{1+\theta\gamma}$ and $\theta = \sigma^2 + \tau^2$ we arrive at $\eta = \dfrac{\tau^2\gamma}{\sigma^2 + \tau^2(1+\gamma)}$. Substituting for σ^2 from (5) gives:

$$\eta = \frac{\tau^2\gamma}{(1-\eta)^2\sigma_x^2 + \tau^2(1+\gamma)} \tag{6}$$

The model suggests that as the variance of aggregate demand shift approaches zero, the value of η approaches $\dfrac{\gamma}{1+\gamma}$ and tends monotonically to zero as the variance of aggregate demand shift approaches infinity. Thus, under a regime of stable inflation and a central bank that is not trading on the Phillips curve, the value of the estimated η is larger than that under a regime of high inflation and a central bank that exploits the Phillips curve. Also, the higher the estimate of η, the more credible the central bank is.

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[10] There are a few assumptions underlying the Lucas model, but not all of them are relevant to this paper. Relevant assumptions are discussed briefly.

The standard predictions of the model are:

First, fully anticipated changes in monetary policy have no effect on real output in the long run, but they induce an inflation bias and increase inflation. This is an unfavourable situation.

Second, unanticipated monetary policy changes surprise suppliers and alter relative prices. Suppliers may decide to increase their production when they observe actual prices higher than their expectations. This increase in real output is short-lived and lasts as long as it takes suppliers to adjust their expectations. Once they are sure that the increase in the price level is a general increase in all prices they cut production. In the long run, there is change in real output, but inflation is higher. This too is an unfavourable situation.

Third, the model predicts that the magnitude of η is larger the smaller the variance of the demand shifts, which depends on the variance of inflation. This means that most of the change in nominal output will show up in high real growth rather than in inflation. If inflation ΔP_t is under control, a rise in nominal output growth will be reflected mainly in a higher real income growth. This is termed a *favourable* trade-off and it is indicative of credibility of the central bank.

I think this model is appropriate because nominal income growth and inflation rates in my sample do not exhibit any persistence particularly during the period of stable inflation rates. But, their variances have changed significantly over the samples. These two stylised facts are crucial to the validity of the model.

3.1 Estimating the model and hypotheses tests

Two approaches are used to estimate the model. A time series estimation for each country and a pooled time-series and cross-sectional. First is the time series estimation, where equation (3) and (4) are estimated *separately* and in an *unrestricted* form:

$$y_{c,t} = a_{11} + a_{12}\Delta x_t + a_{13} y_{c,t-1} + \varepsilon_{1t} \qquad (7)$$

$$\Delta P_t = a_{22}\Delta x_t + a_{23}\Delta x_{t-1} + a_{24}\Delta y_{c,t-1} + \varepsilon_{2t} \qquad (8)$$

Second, equation (3) and (4) are estimated *jointly* as a system and in a *restricted* form. Then equation (7) and (8) are estimated jointly as a system and the cross-equation restrictions in (3) and (4) are tested. Note that equation (4) includes the trend in output. When equation (8) is estimated this trend will be tested. The estimation covers two sub-samples. The first sub-sample covers the periods of disinflation. Equation (8) is estimated with a trend. When the trend is found to be insignificant it is dropped out from the regression. The second sub-sample covers the period of maintained low and stable inflation rates.[11] Note that these samples vary in length from one country to another. The trend is treated in the same fashion when I estimate the system of equations.

[11] I used both a linear trend and a HP filter trend. I found no significant differences. I retained the linear trend.

Equation (7) is the restricted form of (3). Cyclical real output y_{ct} is defined as the log of real GDP minus the log of potential real GDP. The HP filter with a smoothing parameter equal to 1600 is used to estimate potential output.[12] The growth rate of nominal output Δx_t is measured by the log difference of nominal GDP. Equation (8) is the restricted form of (4). The inflation rate ΔP_t is the log difference of the GDP deflator.

Before I estimate the equations, the assumption that nominal output is exogenous is tested. There are many ways of testing it, but the easiest way to test it is to check whether, or not, Δx_t in equations (3) and (4) is white noise. I use the Bartlett's – Kolmogrov - Smirnov test. This is a non-parametric test that is based on measuring the distance between the spectral density function of Δx_t and that of the white noise. I test this assumption for each country over the sub-samples identified earlier. The results are reported in table 2. The results indicate some support to the hypothesis that Δx_t is white noise. For Australia, The hypothesis is rejected in the period before inflation targeting, but it could not be rejected during inflation targeting. This is also the case for Canada and New Zealand. In Sweden and United Kingdom the hypothesis cannot be rejected in both sub-samples. However, the best way to deal with the exogeneity problem is to use IV estimator, which is presented next.

The single equation estimation is accomplished by Ordinary Least Squares method (OLS) unless the residuals are diagnosed with serial correlation. If they are, the maximum likelihood method (ML) with an AR error correction is used instead of OLS. The estimation of the single equations covers two sub-samples. The first group of sub-samples covers periods of high and variable inflation rates. The second group of sub-samples covers periods of maintained low and stable inflation rates as described earlier.

Equation (7) and (8) will fit the data well only if aggregate demand fluctuations dominated the data and if they are the major source of variation in inflation and cyclical output. Although the results are intuitive, they should be interpreted with caution because there are many problems such as small samples and mismeasurements of aggregate demand. The robustness of the results to different models is also a concern.

The results of equation (7) are reported in table 3. Table 3 contains seven columns. The first column lists the country followed by the two sub-samples groups. The coefficients a_{11}, a_{12} and a_{13} are listed in columns 2-4. The p values of the Durbin h and the LM_1 statistics are reported in columns 5-10. The coefficient a_{11} is negative as expected (equivalent to δ in equation 3). The coefficient of interest is a_{12}

[12] The problems of the HP filter discussed in King and Rebelo (1993), Harvey and Jaeger (1993), Cogley and Nason (1995), and Nelson and Kang (1981) are acknowledged. It is also recognised that the smoothing parameter in the HP filter may be different from 1600 for different countries, but these problems are beyond the scope of this paper and will not be addressed. The fact that potential output is an unobserved variable is by itself a major problem.

(equivalent to η in equation 3); its magnitude increases during the periods of inflation targeting in all countries, except for Canada and the United Kingdom. The increase in the magnitude during the periods of inflation targeting is consistent with our previous observations of the data and the Lucas (1973) and the Faust-Svensson (1999) propositions.

The hypothesis that a_{12} is equal across sub-samples is tested and rejected in Australia, New Zealand and Sweden, but not for Canada, and United Kingdom. In other words, during the periods of low and stable inflation regimes, changes in nominal output growth did induce significant increase in real output in Australia, New Zealand and Sweden, but not in Canada and the United Kingdom (statistics are not reported).

The standard errors of the coefficient estimates are reported in parentheses. The goodness of fit in terms of R^2 is very good and the residuals of the equation are serially uncorrelated, which suggests that the regressions not misspecified.

The results of equation (8) are reported in table 4, which has the same format as table 3. Compared with the periods of high inflation, the effect of nominal output growth on the inflation measured by the coefficient a_{22} is smaller in the second sub-sample. Except, in Canada and the United Kingdom. The hypothesis that a_{22} is equal across sub-samples is tested and rejected in all countries except for Canada and the United Kingdom.

Again, the change in the magnitudes of the coefficient a_{22} in the case of New Zealand is remarkable. It declined from 1.06 during the period of high inflation to as little as 0.21 during the period of inflation targeting. As expected, if nominal output growth does not contribute to inflation, the goodness of fit deteriorates during the period of inflation targeting. The residuals are white noise.

Next, the system is estimated with cross-equations restrictions.

3.2 Estimating the system using IV estimator

Now, equation (3) and (4) are estimated simultaneously for each country using the Generalised Method of Moments (GMM), which we hope it solves the endogeneity problem of nominal income.[13] Restrictions cannot be rejected at the 10% level, and the majority cannot be rejected at the 5% level.[14] The results are reported in table 5. The results are consistent with the OLS regressions reported in table 2 and 3 in the

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[13] We do not have a priori assumption about the errors (serially uncorrelated or heteroscedastic) so GMM is used to obtain efficient estimates of the parameters. The instruments are the predetermined variables. Themselves, i.e., nominal output growth, lagged nominal output growth, lagged output gap, lagged changes of the output gap and a constant. The instruments are perfectly correlated with themselves of course, but the fact the errors in the OLS regressions were serially uncorrelated is comforting. Nevertheless, one should improve the diagnostics of the instrument in the future. Correction for small sample is used when the variance of the moment function is estimated Gallant (1987). Over-identifying restrictions are tested using the test statistics of Hansen (1982). Starting values are the coefficients estimated by OLS. A grid search is used. For example, for η, an initial value of 0.2 is used for the first sub-samples and a grid search between zero and one is conducted.

[14] See Gallant and Jorgenson (1979) for testing restrictions on the parameters.

sense that the Wald statistics reject the hypothesis that the η's are stable across sub-samples, except in Canada and the United Kingdom.

Across inflation regimes, the Australian, New Zealand and Swedish cases are unambiguous: a higher nominal output growth has contributed more to a higher real output growth than to a higher inflation. The cases of Canada and the United Kingdoms' results are very stable across regimes. This needs some explanation.

There is no evidence that Australia, New Zealand and Sweden central banks exploit the trade-off between real output and inflation. In general, the results support the Lucas (1973) proposition that expansionary demand policies have less effect on inflation and higher effect on real output in countries when the inflation rate is stable (less variability). The results are also consistent with Faust-Svensson (1999) proposition that a high-credibility central bank conducts less expansionary policies than a low-credibility central bank and induces less inflation.

The evidence from Australia, New Zealand and Sweden seems to suggest that demand expansions (e.g., high money growth) are less inflationary and policies are credible.

In the cases of Canada and the United Kingdom, a regime of low and stable inflation rates is not statistically different from a regime of higher inflation rates. The effect of higher growth rate of nominal GDP on inflation and real output is constant across regimes.

These results are less obvious than those of Australia, New Zealand and Sweden, but do not necessarily imply that these central banks are not credible. *If* those central banks pursued credible policies then stable inflation and aggregate demand must have been *offset* by some other instability. The question is what factor has to change to keep $d\eta = 0$?

To answer the question, take the partial derivatives of η with respect σ, τ and γ using the expression $\eta = \dfrac{\tau^2\gamma}{\sigma^2 + \tau^2(1+\gamma)}$

$$\partial\left(\frac{\tau^2\gamma}{\sigma^2+\tau^2(1+\gamma)}\right)/\partial\tau = 2\tau\gamma\frac{\sigma^2}{(\sigma^2+\tau^2+\tau^2\gamma)^2}$$

$$\partial\left(\frac{\tau^2\gamma}{\sigma^2+\tau^2(1+\gamma)}\right)/\partial\sigma = -2\tau^2\gamma\frac{\sigma}{(\sigma^2+\tau^2+\tau^2\gamma)^2}$$

$$\partial\left(\frac{\tau^2\gamma}{\sigma^2+\tau^2(1+\gamma)}\right)/\partial\gamma = \tau^2\frac{\sigma^2+\tau^2}{(\sigma^2+\tau^2+\tau^2\gamma)^2}$$

Take the total derivative $d\eta = \dfrac{\partial\eta}{\partial\tau}d\tau + \dfrac{\partial\eta}{\partial\sigma}d\sigma$. Let us assume that the central banks of Canada and the United Kingdom are credible in the sense that they do not trade on the Phillips curve. In other words, σ_x^2 is very low. Then we ask the question, given that σ_x^2 is low, what makes $d\eta = 0$? We solve for $d\gamma$ as a function of the partial derivatives, $d\tau$ and $d\sigma$.

$$d\gamma = \frac{-\partial\gamma}{\partial\eta}\left(\frac{\partial\eta}{\partial\tau}d\tau + \frac{\partial\eta}{\partial\sigma}d\sigma\right)$$

$$d\gamma = -\frac{1}{(\tau^2 \frac{\sigma^2+\tau^2}{(\sigma^2+\tau^2+\tau^2\gamma)^2})}\left[d\tau(2\tau\gamma\frac{\sigma^2}{(\sigma^2+\tau^2+\tau^2\gamma)^2}) + d\sigma(-2\tau^2\gamma\frac{\sigma}{(\sigma^2+\tau^2+\tau^2\gamma)^2})\right]$$

For η to remain constant, γ has to decline by the same amount. The decline in γ, given (positive) values of the terms in squared brackets, requires an increase in τ^2, which is the variance of relative price changes. One conclusion is that the variance of relative prices in Canada and the United Kingdom has increased by exactly the same amount of the reduction in σ_x^2 during the period of inflation targeting. A second conclusion in the case of the United Kingdom is that the sample used in estimation is rather short and the Bank of England was only given independence (in the sense of setting interest rate) in 1997. This leaves no degrees of freedom to test its credibility.

Finally, from table 5, it seems that the parameters η, ϕ, δ and β are similar in magnitude and assuming that they remain constant *within* samples over time, a Pooled time-series and cross-section regression may increase efficiency. I estimate the system using pooled time-series and cross-sectional data for the Australia, New Zealand and Sweden. The length of the New Zealand sample restricts the overall sample (1985Q1 to 1998Q1). The sub-samples are the same as described earlier including the same break points. The system of equation (3) and (4) is estimated jointly using GMM. I also tested whether the intercepts (δ) in equation (3) are the same or not. The results are reported in table 6. The hypothesis that the intercepts are equal could not be rejected. Again, the increase in the magnitude of η during the second sub-sample is statistically significant, which indicates that the inflation-targeting regimes are credible in the same manner described earlier. As expected, the effects of potential output trend on inflation differ from on period to another. I report statistically different β's. The pooled time-series and cross-section evidence should reinforce the earlier country's evidence.

4. Summary

Time series and pooled time-series and cross-sectional econometric evidence is found in favour of the propositions in Lucas (1973) and Faust and Svensson (1999): Credible central banks are those which do not exploit the trade-off between real output and inflation, but stabilise aggregate demand shifts by stabilising the inflation rate.

The hypothesis that the Australian, New Zealand, Swedish, Canadian and the United Kingdom central banks are credible is tested using quarterly data from 1983 to 1999. The sample is split into two independent regimes. The first regime includes episodes of high and variable inflation rates and disinflation, while the second regime includes periods of *maintained* low and stable inflation rates. During the fist regime, an increase in nominal output growth increases inflation by more than increasing output. Hence, it is an unfavourable trade-off. During the second regime, an increase in nominal output growth increases real output by more than the inflation rate, which is a favourable trade-off. The evidence suggests that Australian, New Zealand and Swedish regimes are unambiguously credible.

The Canadian and the United Kingdom cases are less obvious. The hypothesis that inflation-targeting regimes are credible could not be confirmed statistically because the effects of nominal output growth on both inflation and real output growth seem to have not significantly changed across regimes. This result actually confirms that these relationships are not simply tautological as some may postulate.

It appears that Canada and the United Kingdom have experienced an increasing volatility in relative prices that *offsets* the decline in the variance of inflation and aggregate demand shifts. In the case of the United Kingdom, the sample used in estimation is rather short and the Bank of England was only given independence (in the sense of setting interest rate) in 1997. This leaves no degrees of freedom to test its credibility.

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Table 1. Descriptive Statistics

	Inflation		Real Income Growth		Nominal output Growth	
	Mean	Variance	Mean	Variance	Mean	Variance
Australia						
(1983:2-1991:4)	6.70	4.56	3.22	7.42	9.25	15.06
(1992:1-1999:2)	1.81	2.06	3.99	1.08	5.41	1.17
Canada						
(1983:1-1991:4)	4.57	0.69	2.86	7.24	6.15	10.42
(1992:1-1998:3)	1.40	0.46	2.73	1.97	3.82	2.48
New Zealand						
(1985:2-1991:4)	8.66	25.35	0.27	2.23	8.95	45.84
(1992:1-1998:1)	1.83	1.02	3.35	3.78	5.01	4.20
Sweden						
(1983:2-1991:4)	7.01	4.42	1.97	2.47	9.14	3.98
(1993:4-1999:2)	1.48	1.62	2.56	2.26	4.44	4.93
United Kingdom						
(1983:1-1991:4)	5.52	3.60	2.70	4.51	8.28	3.70
(1993:4-1999:2)	2.83	0.36	2.93	0.98	5.47	0.88

- Inflation is the annual CPI inflation rate.
- Nominal output growth is GDP growth rate and real income growth is real GDP. All growth rates are annual. Student t statistics

indicate that the means have declined significantly at the 5% level. F tests also indicate that the variances have declined significantly at the 5% level. The statistics are not reported, but they are available upon request. The reduction in the means and the variances are so large one cannot imagine not to reject the null hypotheses. New Zealand experienced no significant changes in the variances of real income growth. Also, in Sweden the variance of nominal output growth did not change. Money growth data are shorter. The data start from 1984, except for New Zealand where they start from 1989.

Table 2. The Bartlett's – Kolmogrov – Smirnov and Q Statistics

	Bartlett's Kolmogrov – Smirnov		Probability of Q at lag 6
	Statistic	95% Critical Value	
Australia			
(1983:2-1991:4)	0.52*	0.34	0.000
(1992:1-1999:2)	0.17	0.37	0.232
Canada			
(1983:1-1991:4)	0.49*	0.33	0.000
(1992:1-1998:3)	0.38	0.39	0.266
New Zealand			
(1985:2-1991:4)	0.60*	0.39	0.002
(1992:1-1998:1)	0.39	0.41	0.746
Sweden			
(1983:2-1991:4)	0.18	0.33	0.694
(1993:4-1999:2)	0.18	0.43	0.968
United Kingdom			
(1983:1-1991:4)	0.24	0.33	0.916
(1993:4-1999:2)	0.23	0.43	0.931

- Computation of the critical values is found in Fuller (1976, p 238).

Table 3

$y_{c,t} = a_{11} + a_{12}\Delta x_t + a_{13} y_{c,t-1} + \varepsilon_{1t}$

Country	a_{11}	a_{12}	a_{13}	R^2	$prob < Dh$	$prob > LM_1$ (ARCH)
Australia						
83:2-91:4	-1.09	0.51	0.88	0.88	0.3654	0.7486
	(0.0001)	*(0.0001)*	*(0.0001)*			
92:1-99:1	-0.89	0.66	0.79	0.85	0.1311	0.1416
	(0.0001)	*(0.0001)*	*(0.0001)*			
Canada						
83:1-91:4	-0.77	0.56	0.90	0.93	0.0661	0.2802
	(0.0001)	*(0.0001)*	*(0.0001)*			
92:1-98:3*	-0.36	0.38	0.89	0.85	NA	0.9174
	(0.0224)	*(0.0005)*	*(0.0001)*			
New Zealand						
85:2-91:4	-0.22	0.10	0.60	0.43	0.0831	0.0631
	(0.4399)	*(0.3553)*	*(0.0037)*			
92:1-98:1	-0.81	0.74	0.97	0.98	0.3059	0.3693
	(0.0001)	*(0.0001)*	*(0.0001)*			
Sweden						
83:1-91:4	-0.59	0.34	0.74	0.61	0.0390	0.6958
	(0.0233)	*(0.0009)*	*(0.0001)*			
93:4-99:1	-0.60	0.71	0.84	0.92	0.1952	0.6312
	(0.0001)	*(0.0001)*	*(0.0001)*			
United Kingdom						
83:1-91:4	-0.99	0.50	0.88	0.91	0.4037	0.9190
	(0.0001)	*(0.0009)*	*(0.0001)*			
93:4-99:1	-0.47	0.46	0.66	0.80	0.1273	0.7689

- Regressions are estimated by OLS.
- Asterisks mean the OLS regression is diagnosed with serial correlation so it is re-estimated by the maximum likelihood method (ML) with AR1 errors.
- NA means that the probability is hard to compute when maximum ML with AR errors is used.
- P values are in parentheses.

Table 4

$\Delta P_t = Trend + a_{22}\,\Delta x_t + a_{23}\Delta x_{t-1} + a_{24}\Delta y_{c,t-1} + \varepsilon_{2t}$

Country	*Trend*	a_{22}	a_{23}	a_{24}	R^2	$prob < DW$	$prob > LM_1$ (ARCH)
Country							
Australia							
83:2-91:4	0.01	0.53	-0.04	0.05	0.91	0.8101	0.5412
	(0.0260)	*(0.0001)*	*(0.7026)*	*(0.7164)*			
92:1-99:1	NA	0.30	-0.07	0.26	0.60	0.6202	0.2276
		(0.09)	*(0.10)*	*(0.18)*			
Canada							
83:1-91:4	0.01	0.22	0.15	-0.08	0.84	0.5785	0.6626
	(0.0190)	*(0.0148)*	*(0.1785)*	*(0.5422)*			
92:1-98:3*	NA	0.50	-0.17	-0.10	0.70	NA	0.7776
		(0.0001)	*(0.739)*	*(0.5810)*			
New Zealand							
85:2-91:4	NA	1.06	-0.13	0.20	0.88	0.4519	0.7827
		(0.0001)	*(0.2360)*	*(0.3078)*			
92:1-98:1	NA	0.21	0.09	-0.11	0.75	0.7493	0.9042
		(0.0014)	*(0.1984)*	*(0.2974)*			
Sweden							
83:1-91:4	0.02	0.58	-0.08	0.34	0.88	0.7899	0.0506
	(0.0085)	*(0.0001)*	*(0.0438)*	*(0.0456)*			
93:4-99:1	NA	0.24	0.15	0.13	0.70	0.7307	0.7539
		(0.0024)	*(0.1997)*	*(0.4219)*			
United Kingdom							
83:1-91:4	0.03	0.46	-0.05	0.04	0.89	0.1644	0.6546
	(0.0001)	*(0.0001)*	*(0.6429)*	*(0.8268)*			
93:4-99:1	NA	0.60	-0.08	-0.28	0.88	0.2056	0.0919
		(0.0001)	*(0.3771)*	*(0.1299)*			

- Regressions are estimated by OLS.
- Asterisks mean the OLS regression is diagnosed with serial correlation so it is re-estimated by the maximum likelihood method (ML) with AR1 errors.
- All regressions for the 1st sub-samples include trend; all the regressions for the 2nd sub-samples don’t.
- P values are in parentheses.

Table 5: GMM estimates
Theoretically Restricted and Unrestricted model

Theoretically restricted model	Unrestricted model
$y_{c,t} = -\delta\,\eta + \eta\,\Delta x_t + \phi\, y_{c,t-1} + u_{1t}$	$y_{c,t} = a_{11} + a_{12}\,\Delta x_t + a_{13}\, y_{c,t-1} + \varepsilon_{1t}$
$\Delta P_t = -\beta\, t + (1-\eta)\,\Delta x_t + \eta\,\Delta x_{t-1} - \phi\,\Delta y_{c,t-1} + u_{2t}$	$\Delta P_t = Trend + a_{22}\,\Delta x_t + a_{23}\,\Delta x_{t-1} + a_{24}\,\Delta y_{c,t-1} + \varepsilon_{2t}$

Country	η	ϕ	δ	β	χ^2_3	*wald* $P > \chi^2_1$ $H_0 : \eta_1 = \eta_2$
Australia						
83:2-91:4	0.18	0.53	-1.24	-0.02	10.03	
	(0.0049)	*(0.0001)*	*(0.2653)*	*(0.0169)*		
92:1-99:1	0.51	0.50	-1.67	NA	8.86	
	(0.0001)	*(0.0001)*	*(0.0001)*			***0.0041***
Canada						
83:1-91:4	0.22	0.70	-0.40	-0.02	6.39	
	(0.0022)	*(0.0001)*	*(0.5916)*	*(0.0154)*		
92:1-98:3	0.25	0.66	-1.20	NA	2.06	
	(0.0004)	*(0.0001)*	*(0.0001)*			***0.7065***
New Zealand						
85:2-91:4	0.05	0.44	-1.25	NA	4.48	
	(0.1612)	*(0.0001)*	*(0.5718)*			
92:1-98:1	0.53	0.85	-1.11	NA	5.84	
	(0.0001)	*(0.0001)*	*(0.0001)*			***0.0001***
Sweden						
83:1-91:4	0.17	0.39	-0.24	-0.01	6.90	
	(0.0169)	*(0.0001)*	*(0.8600)*	*(0.0870)*		
93:4-99:1	0.37	0.39	-1.33	NA	3.25	
	(0.0001)	*(0.0003)*	*(0.0001)*			***0.0561***
United Kingdom						
83:1-91:4	0.38	0.72	-1.62	-0.01	6.92	
	(0.0001)	*(0.0001)*	*(0.0001)*	*(0.0650)*		
93:4-99:1	0.39	0.79	-1.47	NA	7.95	

- The endogenous variables are the output gap and inflation $(y_{ct}, \Delta P_t)$. The rest $(\Delta x_t, \Delta x_{t-1}, y_{c,t-1}, \Delta y_{c,t-1})$ and time trend are predetermined and used as (unique) instruments.
- The Hansen (1982) test statistics for over-identifying restrictions of the instruments are not reported, but they are all insignificant. The P values of t the statistics are in parentheses.
- χ^2 test statistics for the restricted model (Gallant and Jorgenson, 1979). The 5% and 10% critical values with three degrees of freedom are 7.81 and 11.34 respectively.

Table 6: GMM estimates of pooled time-series and cross-sectional data for Australia
New Zealand and Sweden using the restricted model

Sample	η	ϕ	δ	β (Australia)	β (New Zealand)	β (Sweden)
Before inflation targeting (1985:1 – 1991:4)	0.12 (0.0004)	0.49 (0.0001)	-0.53 (0.5583)	-0.15 (0.0011)	0.02 (0.5088)	-0.09 (0.0051)
During inflation targeting (1992:1-1998:1) [a]	0.33 (0.0001)	0.70 (0.0001)	-1.0 (0.0001)	-0.25 (0.0001)	-0.20 (0.0001)	-0.13 (0.0034)
$\chi^2_{1,0.95}$ statistic $H0: \eta_1 = \eta_2$	11.44 (0.0001)					
$\chi^2_{3,0.95}$ statistic [b] $H0: \delta_1(Australia) = \delta_1(NewZealand) = \delta_1(Sweden)$ $H0: \delta_2(Australia) = \delta_2(NewZealand) = \delta_2(Sweden)$	2.96 (0.3978)					

a The last observation is 1998:1 because the New Zealand data end in 1998:1. For Sweden, the inflation-targeting period is 1993:4.
b The hypothesis that country intercepts are equal is tested. The model is estimated with different intercepts then with one intercept for each period, and the hypothesis is tested using Gallant and Jorgenson (1979) χ^2 test by using the change in the least-squares criterion functions. Estimate the full model, the reduced model and subtract the criterion function of the full model from the reduced model.

Figure 1a: Annual Inflation Rates (Australia)

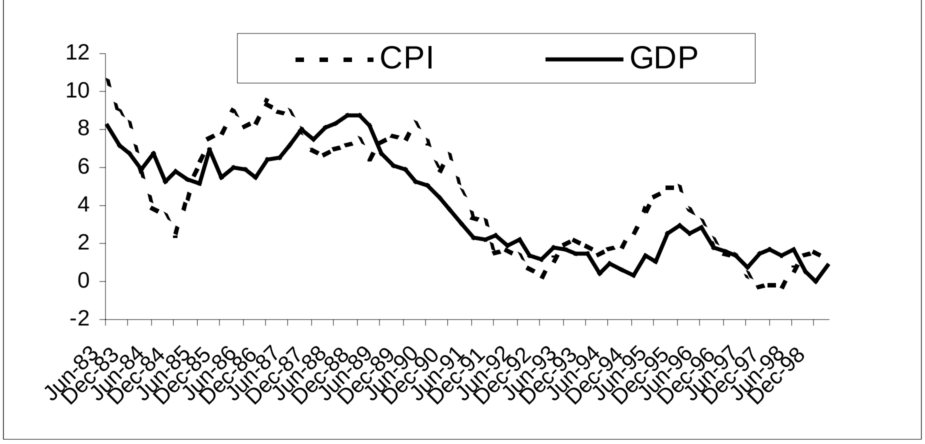


Figure 1b: Annual Inflation Rates (Canada)

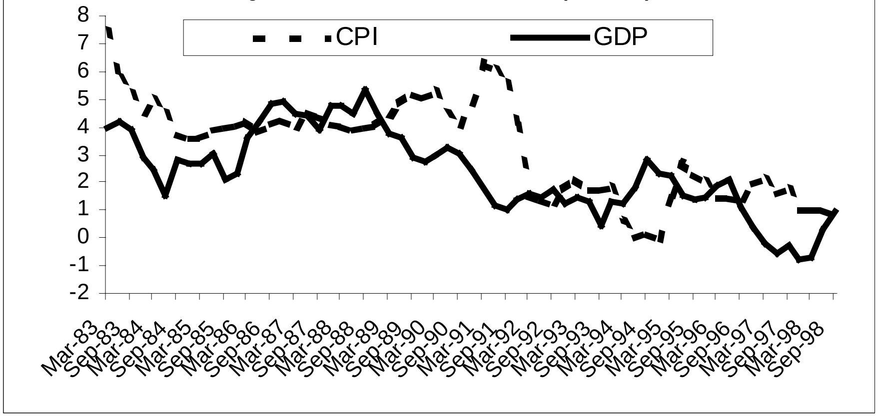
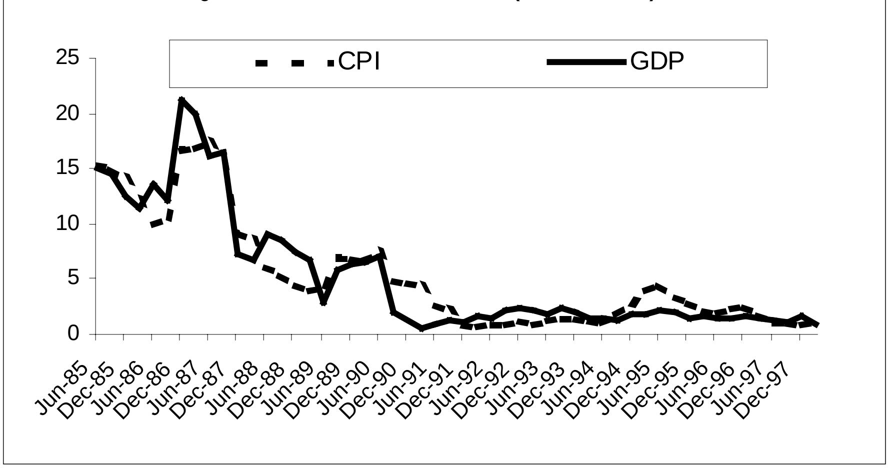


Figure 1c: Annual Inflation Rates (New Zealand)



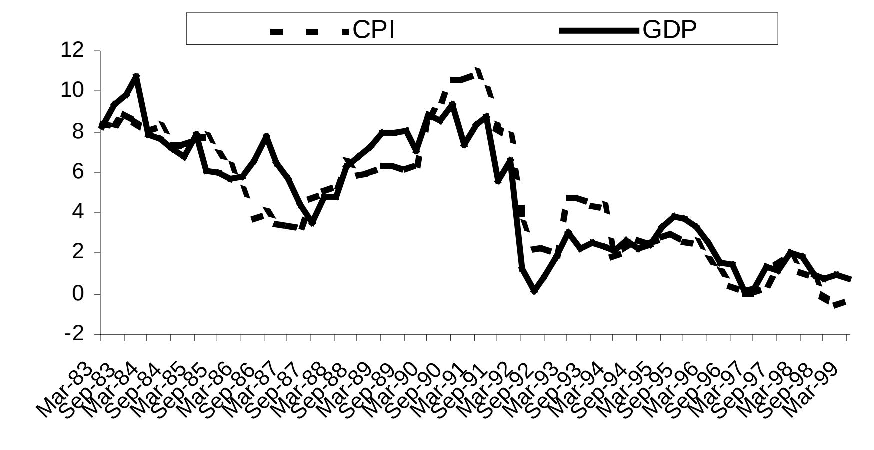


Figure 1d: Annual Inflation Rates (sweden)

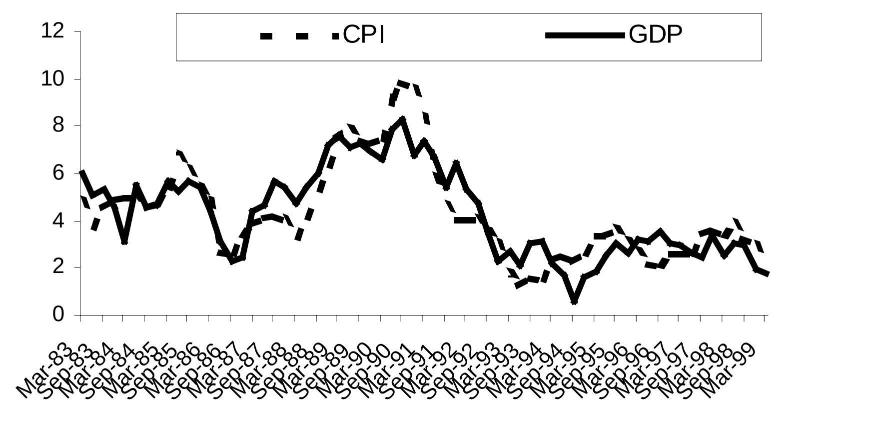


Figure 1e: Annual Inflation Rates (UK)

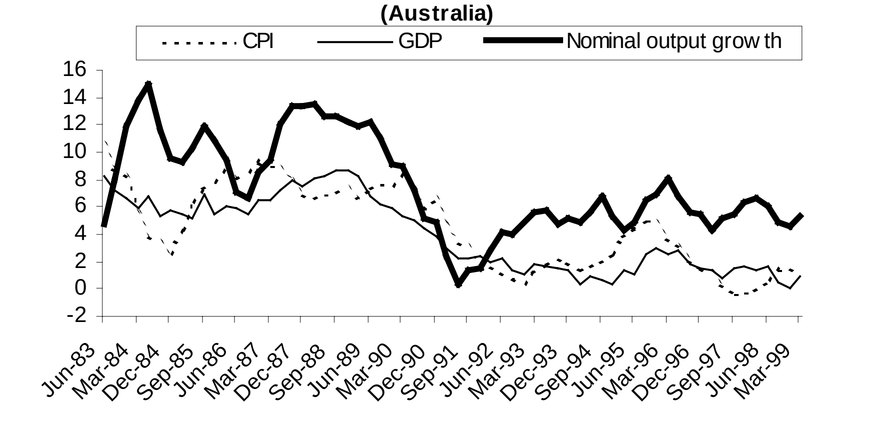


Figure 2a: Annual Inflation Rates & Nominal output Growth (Australia)

Figure 2b: Annual Inflation Rates & Nominal Output Growth (Canada)

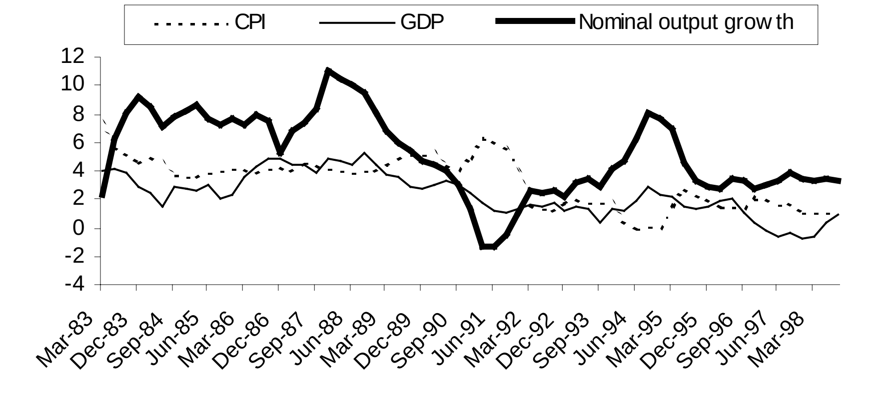


Figure 2c: Annual Inflation rates & Nominal Output Growth (New Zealand)

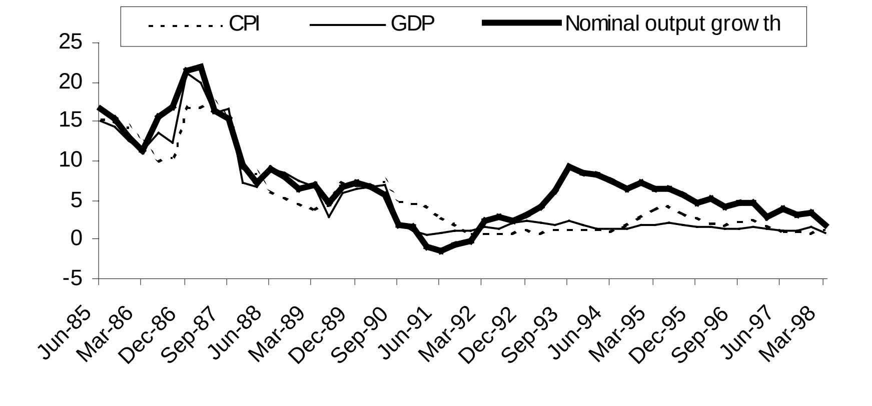


Figure 2d: Annual Inflation Rates & Nominal Output Growth (Sweden)

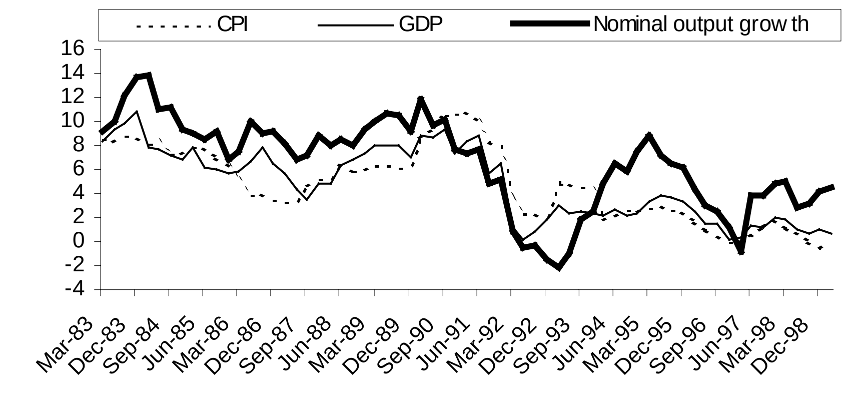


Figure 2e: Annual Inflation Rates & Nominal Output Growth (UK)

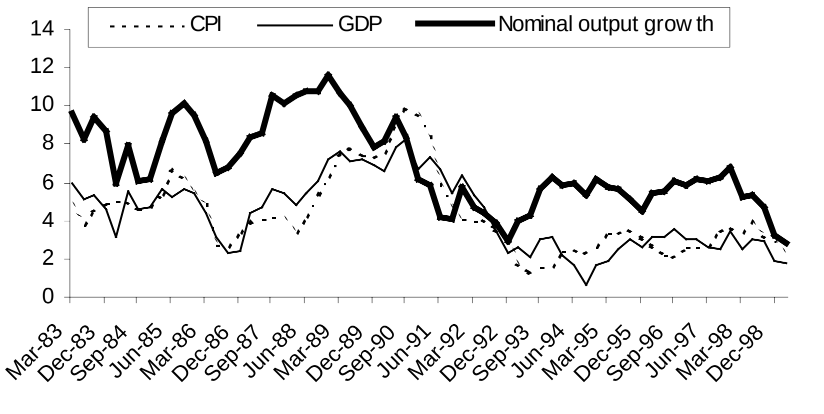


Figure 3a: Nominal & real output growth rates (Australia)

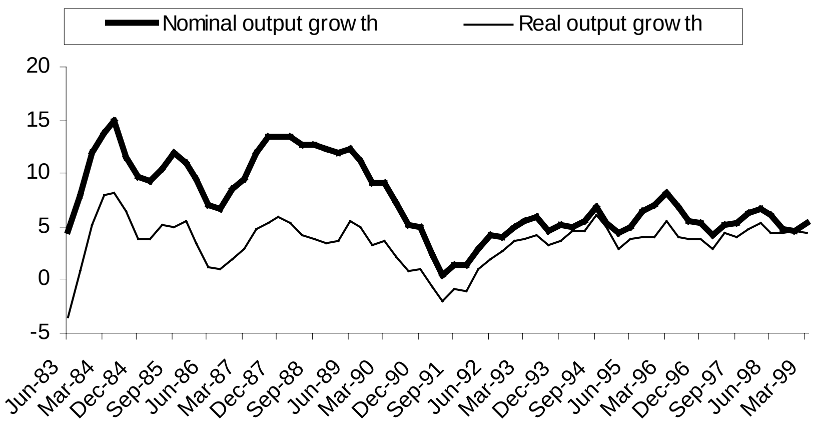


Figure 3b: Nominal & real output growth rates (Canada)

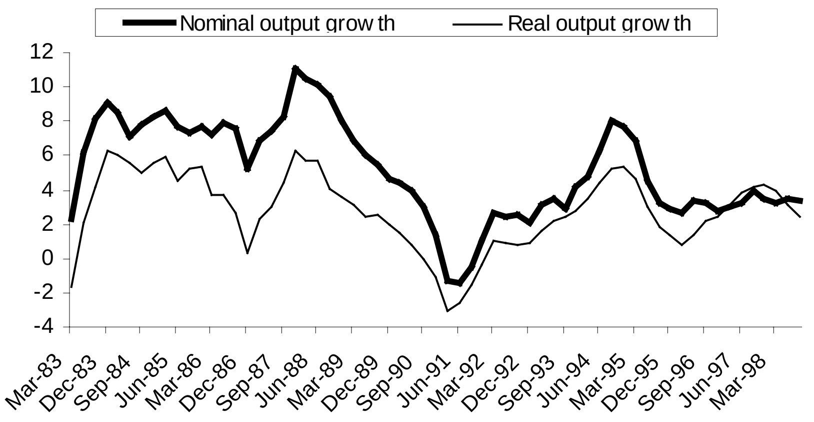


Figure 3c: Nominal & real output growth rates (New Zealand)

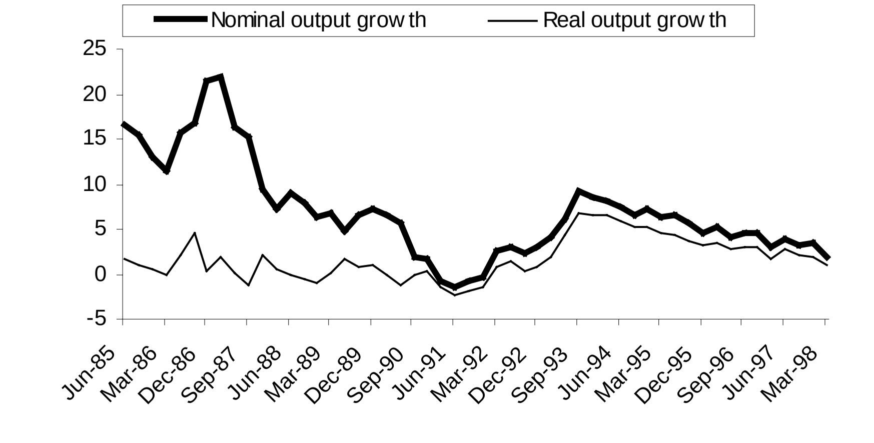


Figure 3D: Nominal & real output growth rates (Sweden)

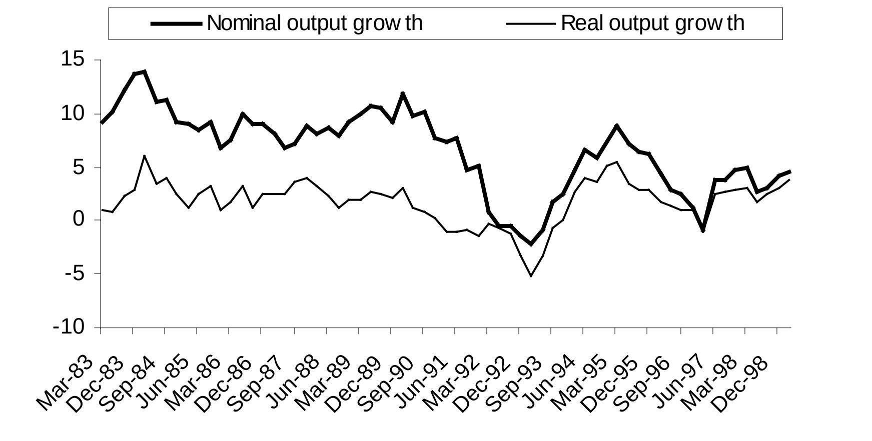
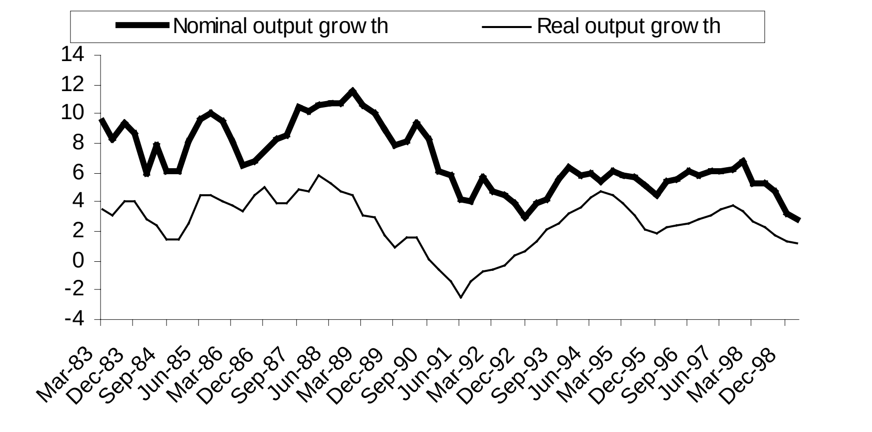


Figure 3e: Nominal &b real output growth rates (UK)



Appendix

Lucas (1973), "Some International Evidence on Output-Inflation Tradeoffs, AER, 326-334.

Let z index markets. And output is decomposed into a normal (secular) component y_{nt} and a cyclical one, which varies from one market to another $y_{ct}(z)$. All variables are in logs.

$$y_t(z) = y_{nt} + y_{ct}(z) \quad (1)$$

The trend reflects capital accumulation and population growth change.

$y_{nt} = \alpha + \beta t$ (This could be modelled differently of course). (2)

The cyclical component varies with perceived relative prices and with its own lagged value.

$$y_{ct}(z) = \gamma[P_t(z) - E(P_t \mid I_t(z)] + \phi y_{c,t-1}(z) \quad (3)$$

The actual price in market z is $P(z)$ at time t and $E_t(P_t \mid I_t(z)$ is the mean current general price level, conditioned on information available in z at time t.

It is assumed that actual price deviates from the geometric economy-wide price level by an amount that is distributed independently of P_t. The percentage deviation of the price level in z from average P_t is denoted z (so that markets are indexed by the their price deviations from average) where z_t is normally distributed, independent of P_t, with mean zero and variance τ^2 ($Cov(P, z) = 0$). The observed log price in z, $P_t(z)$ is the sum of independent normal variates.[15]

$$P_t(z) = P_t + z \quad (4)$$

Rational forecasts

$$E(P_t(z) \mid I_t) = E(P_t \mid I_t) + E(z \mid I_t) = E(P_t \mid I_t) = \overline{P_t} \quad (5)$$

$$Var(P_t(z)) = Var(P_t) + Var(z) + 2Cov(P_t, z) = \sigma_P^2 + \tau^2 \quad (6)$$

$$Cov(P_t(z), P_t) = E[P_t(z) - E(P_t(z) \mid I_t)][P_t - E(P_t \mid I_t)] \quad (7)$$

$$= E[(P_t(z) - \overline{P_t}) - (P_t - \overline{P_t})] \quad (8)$$

15 z is not necessarily a constant.

$$= E[(P_t + z - \overline{P}_t)(P_t - \overline{P}_t)] \quad (9)$$

$$= E(P_t - \overline{P}_t)^2 + E[(z\ )(P_t - \overline{P}_t)] \quad (10)$$

$= \sigma_P^2$ because z and P_t are independent and $\overline{P}_t = \overline{P} =$ a constant.

$$\therefore E(P_t \mid I_t(z)) = \overline{P}_t + \frac{\sigma_P^2}{\sigma_P^2 + \tau^2}(P_t(z) - \overline{P}_t) \quad (11)$$

$$= \frac{\sigma_P^2}{\sigma_P^2 + \tau^2} P_t(z) + \overline{P}_t(1 - \frac{\sigma_P^2}{\sigma_P^2 + \tau^2}) \quad (12)$$

$$= (1 - \frac{\sigma_P^2}{\sigma_P^2 + \tau^2})P_t(z) + (\frac{\sigma_P^2}{\sigma_P^2 + \tau})\overline{P}_t \quad (13)$$

$$(1)\ = (1-\theta)P_t(z) + \theta\overline{P}_t, \text{ where } \theta = \frac{\sigma_P^2}{\sigma_P^2 + \tau^2} \quad (14)$$

Substitute (3) and into (1)

$$y_t(z) = y_{nt} + \gamma[P_t(z) - E(P_t \mid I_t(z)] + \phi y_{c,t-1}(z) \quad (15)$$

And using (5) we get

$$y_t(z) = y_{nt} + \gamma P_t(z) - \gamma[(1-\theta)P_t(z) + \theta\overline{P}_t] + \phi y_{c,t-1}(z) \quad (16)$$

$$y_t(z) = y_{nt} + \theta\gamma[P_t(z) - \overline{P}_t] + \phi y_{c,t-1}(z) \quad (17)$$

From equation (1) we get

$$y_{c,t-1}(z) = y_{t-1}(z) - y_{n,t-1} \quad (18)$$

$$\therefore y_t(z) = y_{nt} + \theta\gamma[P_t(z) - \overline{P}_t] + \phi[y_{t-1}(z) - y_{n,t-1}] \quad (19)$$

Aggregating over all markets, we get the Lucas aggregate supply curve

$$y_t = y_{n,t} + \theta\gamma[P_t - \overline{P}_t] + \phi[y_{t-1} - y_{n,t-1}] \quad (20)$$

The aggregate demand is a simple IS-LM unit elastic

$$y_t + P_t = x_t \quad (21)$$

Equate the aggregate demand to the aggregate supply

$$(x_t - P_t) = y_{nt} + \theta\gamma[P_t - \overline{P}_t] + \phi[y_{t-1} - y_{n,t-1}] \quad (22)$$

$$x_t - y_{nt} + \theta\gamma\overline{P}_t - \phi[y_{t-1} - y_{n,t-1}] = P_t + \theta\gamma P_t \quad (23)$$

$$P_t(1+\theta\gamma) = x_t - y_{nt} + \theta\gamma\overline{P}_t - \phi[y_{t-1} - y_{n,t-1}] \quad (24)$$

$$\overline{P}_t = E(P_t \mid I_t) \tag{25}$$

From the demand equation 21

$$P_t = x_t - y_t \Rightarrow E(P_t \mid I_t) = E(x_t \mid I_t) - E(y_t \mid I_t) \Rightarrow \overline{P}_t = E(x_t \mid I_t) - E(y_t \mid I_t) \tag{26}$$

Δx_t is distributed normal with a mean δ and a variance σ_x^2, thus,

$$E(x_t - x_{t-1} \mid I_t) = \delta \tag{27}$$

$$E(x_t \mid I_t) - E(x_{t-1} \mid I_t) = \delta \tag{28}$$

$$E(x_t \mid I_t) = \delta + x_{t-1} \tag{29}$$

From the aggregate supply equation

$$y_t = y_{n,t} + \theta\gamma[P_t - \overline{P}_t] + \phi[y_{t-1} - y_{n,t-1}] \tag{30}$$

and

$$\begin{aligned} E(y_{nt} \mid I_t) &= y_{nt} \\ E(P_t \mid I_t) &= \overline{P}_t \\ E(y_{t-1} \mid I_t) &= y_{t-1} \end{aligned} \tag{31}$$

$$\therefore E(y_t \mid I_t) = y_{nt} + \phi[y_{t-1} - y_{n,t-1}] \tag{32}$$

Hence

$$P_t(1+\theta\gamma) = x_t - y_{nt} + \theta\gamma(\delta + x_{t-1} - y_{nt} - \phi[y_{t-1} - y_{n,t-1}]) - \phi(y_{t-1} - y_{n,t-1}) \tag{33}$$

$$P_t(1+\theta\gamma) = x_t - y_{nt} + \theta\gamma\delta + \theta\gamma x_{t-1} - \theta\gamma y_{nt} - \theta\gamma\phi(y_{t-1} - y_{n,t-1}) - \phi(y_{t-1} - y_{n,t-1}) \tag{34}$$

$$P_t(1+\theta\gamma) = x_t - (1+\theta\gamma)y_{nt} + \theta\gamma\delta + \theta\gamma x_{t-1} - \phi(1+\theta\gamma)(y_{t-1} - y_{n,t-1}) \tag{35}$$

And

$$P_t = \frac{\theta\gamma\delta}{1+\theta\gamma} + \frac{1}{1+\theta\gamma}x_t + \frac{\theta\gamma}{1+\theta\gamma}x_{t-1} - y_{nt} - \phi(y_{t-1} - y_{n,t-1}) \tag{36}$$

$$P_t = \frac{\theta\gamma\delta}{1+\theta\gamma} + \frac{1}{1+\theta\gamma}x_t + \frac{\theta\gamma}{1+\theta\gamma}x_{t-1} - y_{nt} - \phi y_{t-1} + \phi y_{n,t-1} \tag{37}$$

But

$$y_{nt} = \alpha + \beta t \tag{38}$$

And

$$y_{n,t-1} = \alpha + \beta(t-1) = \alpha + \beta t - \beta = y_{nt} - \beta \qquad (39)$$

$$\therefore \phi y_{n,t-1} - y_{nt} = \phi y_{nt} - \phi\beta - y_{nt} = -(1-\phi)y_{nt} - \phi\beta \qquad (40)$$

Which gives us

$$P_t = \frac{\theta\gamma\delta}{1+\theta\gamma} + \frac{1}{1+\theta\gamma}x_t + \frac{\theta\gamma}{1+\theta\gamma}x_{t-1} - \phi\beta - \phi y_{t-1} - (1-\phi)y_{n,t} \qquad (41)$$

Substitute the above solution into the aggregate demand equation (21) and solve for y_t.

$$y_t = x_t - \frac{\theta\gamma\delta}{1+\theta\gamma} + \phi\beta - \frac{1}{1+\theta\gamma}x_t - \frac{\theta\gamma}{1+\theta\gamma}x_{t-1} + \phi y_{t-1} + (1-\phi)y_{nt} \qquad (42)$$

$$y_t = (1 - \frac{1}{1+\theta\gamma})x_t - \frac{\theta\gamma}{1+\theta\gamma}x_{t-1} + \phi\beta - \frac{\theta\gamma\delta}{1+\theta\gamma} + \phi y_{t-1} + (1-\phi)y_{nt} \qquad (43)$$

$$y_t = (\frac{\theta\gamma}{1+\theta\gamma})x_t - \frac{\theta\gamma}{1+\theta\gamma}x_{t-1} + \phi\beta - \frac{\theta\gamma\delta}{1+\theta\gamma} + \phi y_{t-1} + (1-\phi)y_{nt} \qquad (44)$$

$$y_t = -\frac{\theta\gamma\delta}{1+\theta\gamma} + \phi\beta + \frac{\theta\gamma}{1+\theta\gamma}\Delta x_t + \phi y_{t-1} + (1-\phi)y_{nt} \qquad (45)$$

Now let $\frac{\theta\gamma}{1+\theta\gamma} = \eta$ (46)

$$y_t = -\eta\delta + \eta\Delta x_t + \phi\beta + \phi y_{t-1} + (1-\phi)y_{nt} \qquad (47)$$

And from equation (1)

$$y_{ct} = y_t - y_{nt} \qquad (48)$$

$$y_{ct} = -\eta\delta + \eta\Delta x_t + \phi\beta + \phi y_{t-1} + (1-\phi)y_{nt} - y_{nt} \qquad (49)$$

$$y_{ct} = -\eta\delta + \eta\Delta x_t + \phi\beta + \phi y_{t-1}\phi y_{nt} \qquad (50)$$

Since $y_{n,t-1} = y_{nt} - \beta$ and $y_{nt} = y_{n,t-1} + \beta$ (51)

Therefore,

$$y_{ct} = -\eta\delta + \eta\Delta x_t + \phi\beta + \phi y_{t-1} - \phi(y_{n,t-1} + \beta) \qquad (52)$$

$$y_{ct} = -\eta\delta + \eta\Delta x_t + \phi(y_{t-1} - y_{n,t-1}) \qquad (53)$$

$$\boxed{y_{ct} = -\eta\delta + \eta\Delta x_t + \phi y_{c,t-1}} \qquad (54)$$

The lagged value of P_t from (41)

$$P_{t-1} = \frac{\theta\gamma\delta}{1+\theta\gamma} - \phi\beta + \frac{1}{1+\theta\gamma} x_{t-1} + \frac{\theta\gamma}{1+\theta\gamma} x_{t-2} - \phi y_{t-2} - (1-\phi) y_{n,t-1} \quad (55)$$

Subtracting (55) from (41) yields

$$\Delta P_t = (1-\eta)\Delta x_t + \eta \Delta x_{t-1} - \phi(y_{t-1} - y_{t-2}) - (1-\phi)(y_{nt} - y_{n,t-1}) \quad (56)$$

Again, recall that $y_{nt} = \alpha + \beta t$, $y_{n,t-1} = \alpha + \beta(t-1) = \alpha + \beta t - \beta$ (57)

So $y_{nt} - y_{n,t-1} = \beta$ and $y_{n,t-2} = \alpha + \beta(t-2) = \alpha + \beta t - 2\beta$, (58)

And $y_t = y_{nt} - y_{ct}$, $y_{t-1} = y_{n,t-1} - y_{c,t-1}$ and $y_{t-2} = y_{n,t-2} - y_{c,t-2}$ (59)

$$\therefore y_{t-1} - y_{t-2} = \beta + y_{c,t-1} - y_{c,t-2} = \beta + \Delta y_{c,t-1} \quad (60)$$

Now substitute (60) in (56)

$$\Delta P_t = (1-\eta)\Delta x_t + \eta \Delta x_{t-1} - \phi(\beta + \Delta y_{c,t-1}) - (1-\phi)\beta \quad (61)$$

$$\boxed{\Delta P_t = -\beta + (1-\eta)\Delta x_t + \eta \Delta x_{t-1} - \phi y_{c,t-1}} \quad (62)$$