

# The effects of potential output uncertainty on the performance of simple policy rules

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In this paper, stochastic simulations of the Reserve Bank of New Zealand's macroeconomic model, FPS, are used to examine the implication of uncertainty about potential output for simple efficient policy rules. Three classes of simple policy rules are examined: standard Taylor rules, forward-looking inflation targeting rules and forward-looking inflation targeting rules that include the contemporaneous output gap. The simulation results suggest that being forward-looking, in terms of inflation, can improve the inflation variability performance of Taylor rules. Looking at it from the other direction, including the contemporaneous output gap in forward-looking inflation targeting rules can improve on their performance in terms of output variability. These basic results are qualitatively robust to constraints on instrument variability and uncertainty about potential.

## 1.0 Introduction

With the achievement of low and relatively stable rates of inflation in many industrialised countries, research has been focused on monetary policy implementation strategies, as summarised by policy rules, that minimise the social loss associated with maintaining these hard-earned gains. This work has generally followed two approaches. The first approach, such as that followed in Svensson (1997), starts from a specification of social preferences and then solves for *optimal* policy rules conditional on a specific model of the economy. The second approach, such as that followed in Fuhrer (1994) and Black, Macklem and Rose (1997), recognises the difficulty in accurately assessing social preferences and has built on the Taylor (1979) concept of *efficient* policy rules. Given the model economy, this approach traces out the lowest combinations of inflation and output variance that are achievable by following simple policy rules. The work presented in this paper follows this latter approach and uses stochastic simulations of the Reserve Bank of New Zealand's *Forecasting and Policy System* model (FPS) to trace out the efficient policy frontiers associated with three classes of simple policy rules.

Although optimal policy rules illustrate the very best that policy can achieve, there are several good reasons for limiting the analysis to simple rules. First, as shown in Clarida, Gali and Gertler (1997),

simple rules tend to describe the historical behaviour of monetary authorities quite well. Second, simple rules like those tested in Svensson and Rudebusch (1998) also come very close to achieving the same outcomes as optimal rules. Third, optimal policy rules are generally very complex and as a result they do not offer a convenient framework for communicating the underlying motivation for policy actions to the general public. Finally, as illustrated in Levin, Wieland and Williams (1998), optimal rules will tend to be highly model specific and to the extent that there is considerable uncertainty regarding the true structure of the economy, simple rules may be more robust.

The inflation and output stabilisation properties of three classes of simple rules are examined. The first class is inflation-forecast-based rules (IFB). This class of rule is currently used by several inflation targeting central banks in their economic forecasting and policy analysis models. The second is the standard Taylor (1993) type rule which has gained considerable use throughout the literature because of its ability to describe the historical policy actions of central banks. The third class, a hybrid between the two, is inflation-forecast-based rules with the addition of the contemporaneous output gap (IFB+G). The motivation for including the contemporaneous output gap in an IFB rule comes from the efficacy of Taylor rules at explaining historical behaviour and from research on optimal policy rules. The latter suggests that state variables rather than goal variables should enter policy rules. Examining IFB+G rules test whether IFB rules effectively summarise all the information contained in state variables.

One argument advanced in favour of Taylor rules is that they are operationally superior in the sense that they can be specified in terms of currently observable data. IFB rules, on the other hand, require the policy maker to formulate forecasts of inflation in a very uncertain world. The results in Black, Macklem and Rose (1997) suggest that under shock uncertainty, IFB rules appear to perform slightly better than Taylor rules. However, this considers only one dimension of the uncertainty that policy makers face when formulating forecasts of inflation. Uncertainty about both the structure and the current state of the economy are two additional dimensions of the uncertainty that policymakers must operate under. In addition to comparing the output and inflation stabilisation properties of the three classes of rules considered, the analysis presented in this paper also examines the implications of uncertainty about the current state of the economy's supply capacity.

Estimating the unobservable level of the economy's supply capacity is of critical importance for inflation targeting central banks. Whether central banks follow Taylor type rules or IFB rules, an estimate of the current level of potential output will have a significant impact on current policy settings. The implications of uncertainty about potential output for policy rules have been recently examined in Isard *et al* (1998), Smets (1998) and Wieland (1998). The dimension of uncertainty about the economy's supply capacity examined here most closely parallels that considered in Isard *et al*. It reflects the fact that policy maker's estimates of the economy's supply capacity will have *ex post* serial correlated errors that arise due to the characteristics of the unobserved components modelling techniques most often employed.

The results indicate that the hybrid IFB+G rules deliver the lowest achievable combinations of inflation and output variability. Starting from the perspective of the standard Taylor rule, inflation variability can be improved upon by making the inflation argument forward looking. From the perspective of the IFB rule, adding the contemporaneous output gap improves the output variabil-

ity performance. These results are robust under reasonable constraints on instrument variability and under uncertainty about the current level of the economy's supply capacity.

The remainder of the paper is structured as follows. In section 2, a brief overview of the structure of the FPS model is presented along with the methodology for generating the stochastic disturbances. Efficient policy frontiers under certainty about potential output are presented in section 3. The implications of uncertainty about potential output on these frontiers are examined in section 4. Section 5 contains a brief summary and conclusion.

## 2.0 FPS at a glance<sup>1</sup>

The Forecasting and Policy System (FPS) model describes the interaction of five economic agents: households, firms, government, a foreign sector, and the monetary authority. The model has a two-tiered structure. The first tier is an underlying steady-state structure that determines the long-run equilibrium to which the model will converge. The second tier is the dynamic adjustment structure that traces out how the economy converges towards that long-run equilibrium.

The long-run equilibrium is characterised by a neoclassical balanced growth path. Along that growth path, consumers maximise utility, firms maximise profits and government achieves exogenously-specified targets for debt and expenditures. The foreign sector trades in goods and assets with the domestic economy. Taken together, the actions of these agents determine expenditure flows that support a set of stock equilibrium conditions that underlie the balanced growth path.

The dynamic adjustment process overlaid on the equilibrium structure embodies both "expectational" and "intrinsic" dynamics. Expectational dynamics arise through the interaction of exogenous disturbances, policy actions and private agents' expectations. Policy actions are introduced to re-anchor expectations when exogenous disturbances move the economy away from equilibrium. Because policy actions do not immediately re-anchor private expectations, real variables in the economy must follow disequilibrium paths until expectations return to equilibrium. To capture this notion, expectations are modelled as a linear combination of a backward-looking autoregressive process and a forward-looking model-consistent process. Intrinsic dynamics arise because adjustment is costly. The costs of adjustment are modelled using a polynomial (up to fourth order) adjustment cost framework (see Tinsley (1993)). In addition to expectational and intrinsic dynamics, the behaviour of both the monetary and fiscal authorities also contributes to the overall dynamic adjustment process.

On the supply side, FPS is a single good model. That single good is differentiated in its use by a system of relative prices. Overlaid on this system of relative prices is an inflation process. While inflation can potentially arise from many sources in the model, it is fundamentally the difference between the economy's supply capacity and the demand for goods and services that determines inflation in domestic goods prices. Further, the relationship between goods markets disequilibrium

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<sup>1</sup> See Black, Cassino, Drew, Hansen, Hunt, Rose and Scott (1997) for a more complete description of the FPS model.

and inflation is specified to be asymmetric. Excess demand generates more inflationary pressure than an identical amount of excess supply generates in deflationary pressure.<sup>2</sup> Although direct exchange rate effects have a small impact on domestic prices and, consequently, on expectations,<sup>3</sup> they primarily enter CPI inflation as price level effects.

## 2.1 Households

There are two types of households in the model: “rule-of-thumb” and “forward-looking.” Forward-looking households save, on average, and hold all of the economy’s financial assets. Rule-of-thumb households spend all their disposable income each period and hold no assets. The theoretical core of the household sector is the specification of the optimisation problem for forward-looking households. The specification is based on the overlapping generations framework of Yaari(1965), Blanchard (1985), Weil (1989) and Buiter (1989), but in a discrete time form as in Frenkel and Razin (1992) and Black *et al*(1994). In this framework, the forward-looking household chooses a path for consumption - and a path for savings - that maximises the expected present value of lifetime utility subject to a budget constraint and a fixed probability of death. This basic equilibrium structure is overlaid with polynomial adjustment costs, the influence of monetary policy, an asset disequilibrium term, and an income-cycle effect.

The population size and age structure is determined by the simplest possible demographic assumptions. We assume that new consumers enter according to a fixed birth rate and that existing consumers exit the economy according to the fixed probability of death. For the supply of labour, we assume that each consumer offers a unit of labour services each period. That is, labour is supplied inelastically with respect to the real wage.

## 2.2 The representative firm

The formal introduction of a supply side requires us to go beyond the simple endowment economy of the Blanchard *et al* framework. The firm is modelled very simply in FPS, but, as with the characterisation of the consumer, some extensions are made to capture essential features of the economy. Investment and capital formation are modelled from the perspective of a representative firm. This firm acts to maximise profits subject to the usual accumulation constraints. Firms are assumed to be perfectly competitive, with free entry and exit to markets. Firms produce output, pay wages for labour input, and make rental payments for capital input.<sup>4</sup> The production technology is Cobb-Douglas, with constant returns to scale.

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<sup>2</sup> Although the body of empirical evidence supporting asymmetry in the inflation process in both New Zealand and elsewhere is growing, the most convincing argument for using asymmetric policy models is the prudence argument present in Laxton, Rose and Tetlow (1994).

<sup>3</sup> The direct exchange rate effect on domestic prices is assumed to arise through competitive pressures.

<sup>4</sup> We also assume that households own the capital stock.

Profit maximisation is sufficient to determine the level of output, the level of employment, and the real wage. FPS extends this framework in a number of directions as firms face adjustment costs for capital and a time-to-build constraint.

### 2.3 The government

Government has the power to collect taxes, raise debt, make transfer payments, and purchase output. As with households and firms, the structure of the model requires clear objectives for government in the long run. However, whereas households' and firms' objectives arise through explicit maximisation, we directly impose fiscal policy choices for debt and expenditure. The government's binding intertemporal budget constraint is used to solve for the labour income tax rate that supports the fiscal choices. The interactions of debt, spending and taxes create powerful effects throughout the rest of the model; government is non-neutral.

### 2.4 The foreign sector

The foreign sector is treated as completely exogenous to the domestic economy. It supplies the domestic economy with imported goods and purchases the domestic economy's exports and thus completes the demand side of the model. Further, the foreign sector stands ready to purchase assets from or sell assets to domestic households depending on whether households choose to be net debtors or net creditors relative to the rest of the world. Several key prices affecting the domestic economy are also determined in the foreign sector. The foreign dollar prices of traded goods and the risk-free real interest rate are assumed to be determined in the foreign sector.

### 2.5 The monetary authority

The monetary authority effectively closes the model by enforcing a nominal anchor. Its behaviour is modelled by a forward-looking reaction function that moves the short-term nominal interest rate in response to projected deviations of inflation from an exogenously specified target rate, an IFB rule. The base case reaction function can be expressed as:

$$rs_t - rl_t = rs_t^* - rl_t^* + \sum_{i=1}^3 1.4 (\pi_{t+i}^e - \pi^T), \quad (1)$$

where  $rs$  and  $rl$  are short and long nominal interest rates, respectively;  $rs^*$  and  $rl^*$  are their equilibrium equivalents;  $\pi_{t+i}^e$  is the model consistent projection of inflation  $i$  quarters ahead, and  $\pi^T$  is the policy target.<sup>5</sup> Although the reaction function is *ad hoc* in the sense that it is not the solution to a well-defined optimal control problem as in Svensson (1996), its design is not arbitrary. The forward-looking nature of the reaction function respects the lags in the economy between policy

<sup>5</sup> The terms of the current Policy Targets Agreement, signed between the Governor of the Reserve Bank of New Zealand and the Treasurer, dictates that the Reserve Bank target an inflation *band* of 0-3%. In the base-case version of FPS, the policy target is the mid-point of this band, 1.5%.

actions and their subsequent implications for inflation outcomes. Further, the strength of the policy response to projected deviations in inflation (1.4) implicitly embodies the notion that the monetary authority is not single minded in its pursuit of the inflation target. Other factors such as the variability of its instrument and of the real economy are also of concern.

FPS is a useful tool for examining the implications of alternative policy reaction functions because agents' expectations are influenced by policy actions. This results from expectations being modelled as a linear combination of a backward-looking autoregressive process and a forward-looking model-consistent process. Modelling expectations in this way partially addresses the critique, initially raised in Lucas (1976), that examining alternative policy actions in reduced-form econometric models gives misleading conclusions.<sup>6</sup> However, a more explicit modelling of agents' learning behaviour would be required to fully address the Lucas critique.

## 2.6 Stochastic simulations with FPS

Running stochastic simulations with a calibrated model is not as straightforward as with an estimated model. For an estimated model, the properties of the residuals from the estimated equations can be used to pin down the distributions for the shocks that are randomly generated. No such residuals exist for a calibrated model. To generate the shocks used for stochastic simulations of FPS we follow a procedure similar to that used in Black, Macklem and Rose (1997). Essentially, the impulse response functions (IRFs) from an estimated VAR are used to calculate the paths for the shocks appearing in the calibrated model's equations. (A more detailed discussion of the methodology can be found in appendix 1.)

This approach has attractive features as well as weaknesses. First, the VAR itself is a reasonably complete representation of the economy and as such captures most of the key temporary disturbances. The VAR approach also leads to shock terms that capture both the serial and cross correlations in the data. The shocks are not interpreted as deep structural shocks, but as summary measures of all the deep structural disturbances that impact the economy at a micro level and, consequently, they should not be expected to be white noise. Because of the limitations of the New Zealand data, we were unable to estimate a reasonable VAR that include a measure of the supply side. Consequently our application of the VAR technique captures only temporary disturbances. Further, we treat the impulses as if they contain purely exogenous disturbances to the economy over the first four quarters. However, even over this horizon the impulses may be capturing some effects from the historical response of policy.

One metric for measuring how well the approach is capturing the stochastic behaviour of the New Zealand economy is to compare the simulated moments from the model with the historical experience. However, given the limitations of New Zealand data, one should be cautious about expecting

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<sup>6</sup> The Lucas critique states that the estimated parameters of such reduced-form models are dependent on the policy regimes in place over the estimation period. Consequently, simulating reduced-form models in which behaviour is invariant to policy actions produces misleading policy conclusions.

these moments to match very closely. In fact, given that FPS has been calibrated to try to look through the effects that considerable structural change has had on the time-series properties of the data, one might even be dismayed if the moments matched too closely. Examining the moments from 100 draws<sup>7</sup> using the base-case FPS reaction function indicates that the VAR methodology yields results broadly consistent with New Zealand's historical experience. In table 1, the standard deviations for key macro variables under the base-case FPS reaction function are compared to the historical experience over two sample periods, 1985 to 1997 and 1988 to 1997. The latter period corresponds to the period of inflation targeting. Year-over-year CPI inflation is denoted by  $\pi^{cpi}$ , real output is denoted by  $y$ , the nominal short-term interest rate is denoted by  $r_s$ , and  $z$  denotes the real exchange rate. Model-generated moments are presented as standard deviations as are historical inflation and the nominal interest rate. The real exchange rate is presented as the standard deviation around a linear time trend and the real output standard deviation is calculated relative to potential output.<sup>8</sup>

Under the base-case FPS reaction function, output variability is higher and inflation variability is lower. This suggests that the base-case rule targets inflation more strictly than has been the case historically. Re-running the 100 draw experiment with a milder policy response to projected deviations of inflation from control, produces variability in inflation that is closer to the historical experience, however, the real output variability generated by the model remains higher than the historical variability.

**Table 1**

**Standard Deviations**

	$\pi^{cpi}$	$y$	$r_s$	$z$
<b>Model Generated Moments</b>				
Base-case response	1.1	2.9	4.4	5.3
Milder policy response	1.5	2.9	3.2	4.8
<b>Historical Experience</b>				
1985 - 1997	3.9	1.7	5.7	5.0
1988 - 1997	1.7	1.8	3.3	3.5

<sup>7</sup> In order to determine the appropriate numbers of draws, we examined the behaviour of the model's moments as the number of draws were increased. Under a range of policy rules, the results illustrated that the moments did not stabilise until the number of draws reached 70 to 80. Consequently, we choose 100 draws to ensure that the moments were stable enough to allow for sensible comparison.

<sup>8</sup> The historical measure of potential output comes from a multivariate filtering technique. The standard Hodrick-Prescott filter is augmented with conditioning information from a Phillips curve relationship, an Okun's law relationship and a survey measure of capacity utilisation. A complete description of the methodology can be found in Conway and Hunt (1997).

A comparison to the historical experience would ideally be done with the moments that the model would generate under a policy rule identical to that actually followed historically. However, this is not actually feasible given that policy was probably conducted under several different policy rules from 1985 to 1997. Using a rule with a milder policy response and considering the 1988 to 1997 inflation targeting period is one simple attempt to try to more accurately reflect actual historical policy. Clearly more work could be done on the characterisation of historical policy to further improve the degree of comfort with the technique.

### 3.0 Efficient policy rules under certainty about potential output

In this section, three classes of policy rules are examined: inflation-forecast-based rules (IFB), standard Taylor rules, and inflation-forecast-based rules that include a contemporaneous output gap term (IFB+G). The efficient frontier for each class is traced out and the resulting frontiers are compared. Consistent with Taylor (1979), the efficient frontier is defined to be the locus of the lowest achievable combinations of inflation and output variability.

#### 3.1 Inflation-forecast-based (IFB) rules

IFB rules comprise the first class of rules examined. These rules adjust the policy instrument in response to a model-consistent projection of the deviation of inflation from its target rate. The base-case FPS policy reaction function falls within this class of rules. Although its design predates Reserve Bank research on efficient policy rules, the FPS base-case rule was not chosen arbitrarily. A recognition of the lags between policy actions and inflation outcomes motivates its forward-looking nature. The magnitude of the policy reaction to the projected deviation of inflation from target reflects the fact that monetary policy is also concerned about the variability in real output and policy instruments in addition to inflation. This class of reaction functions can be expressed as

$$rs_t - rl_t = rs_t^* - rl_t^* + \sum_{i=1}^j \theta_i (\pi_{t+i}^e - \pi^T), \quad (2)$$

where  $rs$  and  $rl$  are short and long nominal interest rates, respectively;  $rs^*$  and  $rl^*$  are their equilibrium equivalents;  $\pi_{t+i}^e$  is the model consistent projection of inflation  $i$  quarters ahead, and  $\pi^T$  is the policy target.<sup>9</sup> The number of leads,  $j$ , and the weights on them,  $\theta_i$ , are a calibration choice.

To trace out the efficient frontiers, a grid search technique is followed. In the base-case version of FPS, the reaction function adjusts the policy instrument in response to the projected deviations of inflation from target six, seven and eight quarters ahead. The weights on the projected deviations of inflation from target are set at 1.4. To determine the set of efficient policy rules, both the magnitudes of the weights and the forward-looking policy horizon are searched over. The forward-

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<sup>9</sup> The terms of the current Policy Targets Agreement, signed between the Governor of the Reserve Bank of New Zealand and the Treasurer, dictates that the Reserve Bank target an inflation *band* of 0-3%. In the base-case version of FPS, the policy target is the mid-point of this band, 1.5%.



looking policy horizon is a three-quarter moving window starting from one quarter ahead and extending to twelve quarters ahead (ten different windows in all). The weights,  $\theta_i$ , range in value from 0.5 to 20. For each rule considered, the resulting moments are calculated by averaging the results from 100 draws, each of which is simulated over a 25 year horizon.<sup>10</sup> The resulting output/CPI inflation variability pairs are graphed in figure 1.

The measures of variability used are the root mean squared deviation (RMSD) of inflation from its target rate and output from potential output. The asymmetry in the interaction of goods market disequilibrium and inflation in FPS suggests that this is the most appropriate measure of variability to use. The consequences of the asymmetric inflation process under stochastic disturbances is that inflation tends on average to be above target and output tends on average to be below its deterministic steady state.<sup>11</sup> Relative to the standard deviation statistic, the RMSD statistic penalises policy rules that result in inflation being more above the inflation target and output being further below its deterministic steady-state level.

The thin line labelled  $\theta = 1$  in figure 1 traces out the result from holding the weight on the projected deviation of inflation from its target rate fixed at 1 and varying the forward-looking targeting horizon. At point A, the targeting horizon is one, two and three quarters ahead. Moving from point A to point B, the forward-looking horizon is extended through to five, six and seven quarters ahead and the variability in both inflation and output are reduced. As the targeting horizon is extended beyond that point, the variability in output is reduced, but only at the expense of increased variability in inflation.

The thin line labelled  $\theta = 1.4$  traces out the results of increasing the weight on the projected inflation gap from to 1.4, and again varying the forward-looking horizon. Increasing the weight reduces inflation variability and output variability for rules targeting at the horizon of 5 quarters and beyond. However for rules targeting at horizons less than five quarters, output variability increases as inflation variability is reduced. As the weights increase, the forward-looking horizon at which both inflation and output variability can be reduced lengthens. Once the weights reach a level of 6, reduced inflation variability can only be achieved at the expense of increased output variability at all forward-looking horizons examined. This is the point where the thick line starts to trace out the globally efficient frontier for all IFB rules examined.

The results show that the base-case FPS rule lies within the efficient frontier. An example of an efficient outcome is point C, with a weight of 7 and a targeting horizon of eight, nine and ten quarters ahead. Under this rule, the resulting RMSDs in inflation from target suggest that 90 percent of the time inflation can be maintained within roughly a 3 percentage point band.<sup>12</sup>

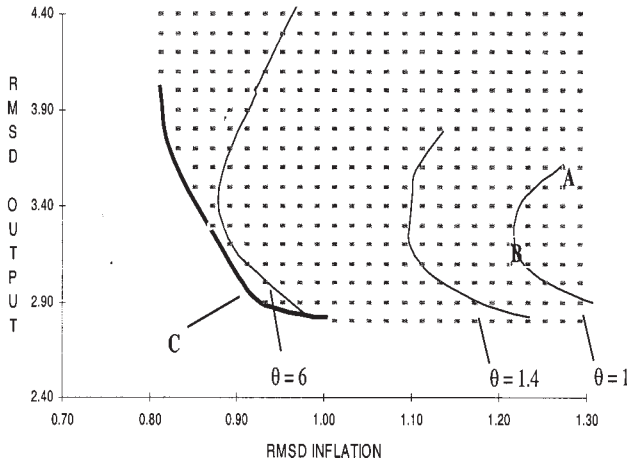
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<sup>10</sup> Consistent with the suggestion in Bryant, Hooper and Mann (1993), the first five years of simulation results are ignored when computing the summary statistics.

<sup>11</sup> For an informed discussions of why the stochastic steady state for output is below the deterministic equilibrium, see Laxton, Rose and Tetlow (1994) and Debelle and Laxton (1997).

<sup>12</sup> This is calculated as  $0.9 \cdot 1.67 \cdot 2$ . We note that this is very similar to the results found in Turner (1996) for New Zealand.

Figure 1  
IFB Rules



### 3.2 Taylor rules

The second class of rules examined is Taylor rules.<sup>13</sup> The policy instrument in this class of rules responds to the contemporaneous deviations of inflation from its target rate and output from potential. This is implied by the rule

$$rs_t - rl_t = rs_t^* - rl_t^* + \theta(\pi_t - \pi^T) + \delta(y_t - yp_t), \quad (3)$$

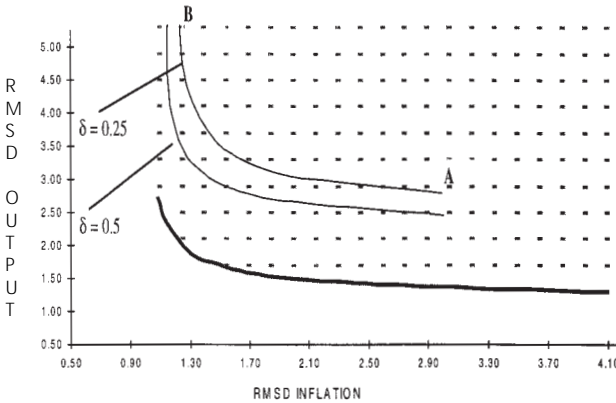
where  $y_t$  is the log of real output,  $yp_t$  is the log of potential output and  $\theta$  and  $\delta$  are response coefficients. To trace out the efficient frontier under Taylor rules, six weights on the contemporaneous output gap ranging from 0.25 to 10 are examined in combination with 9 weights on the contemporaneous deviation of inflation from target ranging from 0.5 to 10.

The inflation/output variability pairs achieved under Taylor rules are graphed in figure 2. Considering a Taylor rule with the weight on the contemporaneous output gap held fixed and increasing the weight on the deviation of inflation from target illustrates the well-documented inflation/output variability trade-off. The thin line labelled  $\delta = 0.25$  in figure 2 traces out the outcomes holding the

<sup>13</sup> These rules are not strict Taylor rules in the sense that a large number of weight on the output gap and inflation are considered not just the weights originally recommended in Taylor (1993).

weight on the output gap fixed at 0.25 and increasing the weight on the inflation gap from 0.5 to 10. Point A has an inflation gap coefficient of 0.5. Moving along the line to point B this weight is increased gradually to 10. Increasing  $\delta$  to 0.5 shifts the trade-off curve towards the origin as illustrated by the thin line labelled  $\delta = 0.5$ . Increasing  $\delta$  up to a value of 6 continues to shift the trade off towards the origin, however, no appreciable shifts occur with larger than 6.

**Figure 2**  
**Taylor rules**



Relative to the frontier achievable under IFB rules, Taylor rules are able to achieve notably lower output variability, but not as low inflation variability regardless of the weight put on the contemporaneous deviation of inflation from target.

### 3.3 Including a contemporaneous output gap in inflation forecast based rules

The final class of rules examined combines aspects of the IFB rules and Taylor rules by including the contemporaneous deviation of output from potential in IFB rules. This class of rules is given by

$$rs_t - rl_t = rs_t^* - rl_t^* + \sum_{i=1}^L \theta_i (\pi_{t+i}^e - \pi^T) + \delta (y_t - yp_t). \quad (4)$$

To make the required simulation task manageable, we search over fewer horizons and weights on the forward-looking inflation gap.<sup>14</sup> Consequently, the frontiers examined here are traced out with slightly fewer observations than for the IFB rules. As was done with the standard Taylor rules 6, alternative values for  $\delta$  are examined ranging from 0.25 to 10.

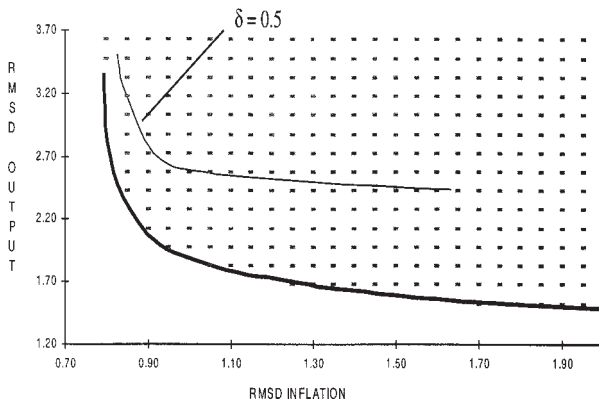
<sup>14</sup> The number of weights on the forward-looking inflation gaps are reduced to 10 from 17 and the number of forward-looking horizon windows are reduced to 6 from 10.

Consistent with the results under the standard Taylor rules, adding the contemporaneous output gap to the IFB rules shifts the frontier downwards. Relative to the IFB frontier in figure 1, the efficient frontiers traced out in figure 3 illustrate that for a given level of CPI inflation variability, output variability can be reduced by responding to the contemporaneous output gap in addition to the forward-looking deviation of inflation from target. For example, achieving a RMSD on inflation variability of 1.0, including the standard Taylor weight of 0.5 on the output gap term reduces output variability from 2.8 to 2.6. The larger is the weight on the output gap, the more output variability can be reduced. Increasing that weight to 1.5 reduces the RMSD of output to 2.2. With a response coefficient of 10, the RMSD of output can be reduced to 1.9.<sup>15</sup>

Comparing these results to those achieved under Taylor rules illustrates the benefits of being forward looking in terms of the inflation gap that policy responds to. Under IFB+G rules inflation variability is notably reduced relative to that achievable under Taylor rules.

These results are different than those found in Haldane and Batini (1998), where the inclusion of the contemporaneous output gap did not shift the efficient frontier downwards as it does here. The Haldane and Batini result lead the authors to conclude that IFB rules were “output encompassing.” In addition to the obvious potential source of the conflicting results being model specification differences, a possible explanation is that in Haldane and Batini the search over rule specification is not quite as general as is done here. The contemporaneous output gap term was included in a rule

**Figure 3**  
**IFB+G rules**



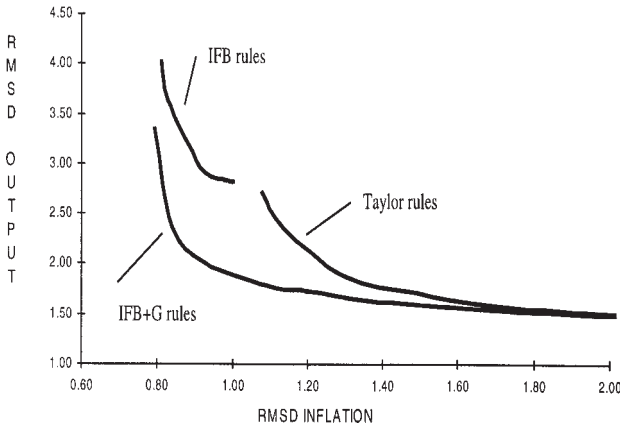
<sup>15</sup> This reduction in output variability eventually comes at a significant cost in terms of increased variability in instruments. The increases in the RMSD in nominal interest rates is relatively minor with the low weights on the output gap. With the weights of 0.5 and 1.5 on the contemporaneous output gap the RMSD in nominal interest rates increases from 5.1 to 5.2 and 6.6 respectively. However, very large weights on the output gap term result in dramatic increases in instrument variability. The largest weight considered, 10, resulted in the RMSD of the nominal short-term interest rate increasing to 22.

that had the horizon and weight optimised in the absence of an output gap term. It is possible that a more general search technique would have yielded different results.

### 3.4 Comparing the three classes of policy rules

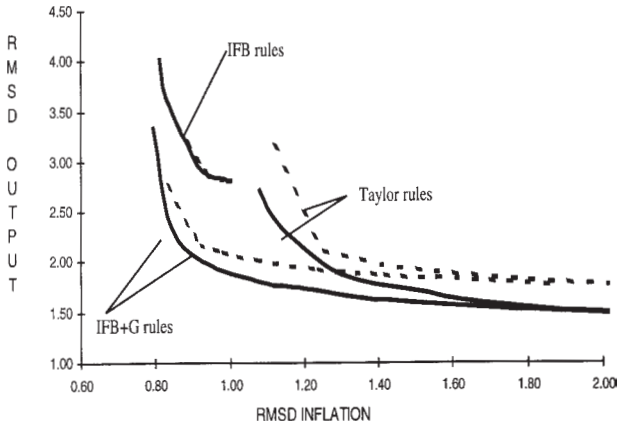
The results presented here indicate that standard Taylor rules and the inclusion of the contemporaneous output gap in IFB rules yield inflation/output variability options not achievable under pure forward-looking inflation targeting rules. In figure 4, the achievable frontiers under the three classes of policy rules are compared. Relative to pure IFB rules, standard Taylor rules allow for significant improvements in output variability although they cannot achieve the same inflation variability performance. Including the contemporaneous output gap in IFB rules allows for a similar reduction in output variability, without sacrificing inflation variability performance.

**Figure 4**  
Comparing the efficient frontiers



One important implication of achieving this reduced output variability under these rules is that instrument variability often dramatically increases. In many cases this variability would imply that nominal short-term interest rates would often be required to be negative. This is clearly not feasible. In similar experiments with a simple demand side version of FPS, imposing a non-negativity constraint on nominal interest rates constrains the variability in nominal interest rates such that their RMSD never exceeds 8.0. The dashed lines in figure 5 trace out the efficient frontiers that result from considering only the policy rules that result in instrument variability consistent with a non-negativity constraint. This constraint slightly reduce the output variability performance of the rules that include the contemporaneous output gap.

**Figure 5**  
**Effect of instrument variability constraints**



#### 4.0 The implications of uncertainty about potential output

One criticism that is often directed at IFB rules is that they require the policymaker to formulate a forecast of future inflation in a very uncertain world (see for example McCallum and Nelson (1998)). The policymaker is uncertain about the true structure of the economy, the nature of the disturbances that are likely to occur, and the underlying state of the economy and how it is likely to evolve over the forecast horizon. These are all legitimate concerns that policymakers need to address. In this section, the implications of the policymaker's uncertainty about one aspect of the state of the economy, its supply capacity, are examined. This is important both for IFB rules and rules that include the contemporaneous output gap.

#### 4.1 Incorporating uncertainty

To examine the implications of uncertainty about potential output it is necessary to derive a characterisation of what the policymaker's typical errors about potential output might look like. Methods for estimating the contemporaneous level of potential output used by policymakers often rely on techniques for decomposing real output data into their trend (supply) and cyclical (temporary) components. Examples of these techniques used by policymakers that rely on a variant of the Hodrick Prescott (1997) filter can be found in Laxton and Tetlow (1992), Butler (1996), Haltmaier (1996), and Conway and Hunt (1997). Harvey and Jaeger (1993) illustrates that the Hodrick-Prescott (HP) filter is a particular restricted version of an unobserved components model.

The uncertainty about how accurately estimates from unobserved components models reflect the true level of potential output has been shown in Kuttner (1994) to arise from two sources. The first is "filter" or "signal extraction" uncertainty. This arise because even if the parameters of the model

are known with certainty, the unobserved state variable still has a noisy link to the data and the estimate must be extracted given the available data set. The second source is “parameter” uncertainty. The parameters of unobserved components models are estimated using the Kalman recursion and maximum likelihood techniques. The estimated parameters thus have associated variances. The dimension of uncertainty that is examined here is the former rather than the latter. Specifically, we consider the implications that HP filter uncertainty about the monetary authority’s estimate of potential output has on the relative performance of the simple policy rules examined.

A multi-step procedure is used to generate the time series paths for the errors about potential output arising from HP filter uncertainty. The model is first simulated under the set of seeded disturbances used to generate the 100 draws used in the experiments under consideration. Policy is characterised as the FPS base-case policy rule and potential output is assumed to be known with certainty. To extract the proxy for the monetary authority’s typical errors associated with filter uncertainty, the resulting times-series paths for real output from each draw are detrended using the HP filter in two ways. First, the HP filter is run as a true filter through data using only data up to time  $t$  to extract the estimate of potential output at time  $t$ . Next it is run as a smoother using the complete data set up to time  $T$  to extract estimates of potential output for all  $t$ . The monetary authority’s error about potential output is the difference between the filter estimate and the smoother estimate. As noted in Kuttner (1994) the smoother can be used in this way to extract the level of filter uncertainty associated with the unobserved components model.

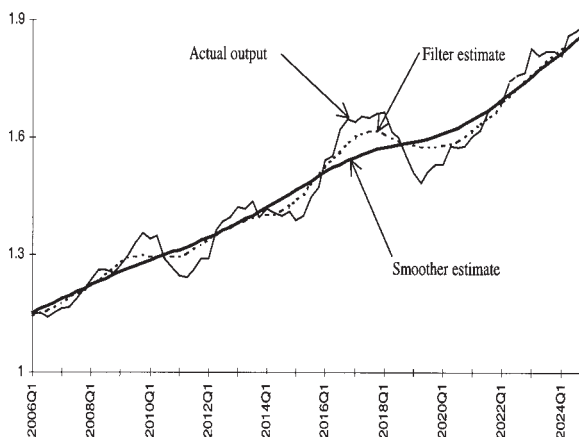
Running the HP filter as a true filter is meant to proxy how a monetary authority might extract an estimate of current potential output. However, before the filter is applied to extract the date  $t$  estimate, four quarters of estimated data points are added to the real output series using the correct *average* growth rate in potential output. This is done because a straight application of the H-P filter without making any adjustment for the end-point problem associated with using it as a straight filter would be too naive a characterisation of most monetary authority’s estimation techniques. As outlined in Butler (1996) and Conway and Hunt (1997) estimation techniques based around the HP filter apply various extensions to mitigate some of the filter uncertainty in the end-of-sample estimates. Even extending the data, as is done here, is probably too naive relative to actual estimation techniques, but it has the virtue of simplicity.

These estimated errors are incorporated into the forward-path solution technique in the following way. In period  $t$  the monetary authority sets policy using the true model of the economy to generate a forecast of inflation based on its view about the current level of potential output, lagged information on the all the model outcomes and all the current period’s *temporary* disturbances. For simulation purposes, potential output evolves according to a fixed growth rate in the monetary authority’s forecasting framework. The policy setting solved for within this framework is then sent to the real world along with all the temporary disturbances *plus* the error on potential output as estimated above. Given the policy settings, the temporary shocks and the correct level of potential, the model solves for the actual outcome. The process is updated one quarter to date  $t+1$  and the monetary authority sets policy again. The monetary authority receives some feedback that it made an error in that real outcomes and inflation were not as it expected for date  $t$ ; however, it persists with its view of how potential output evolves. In this set up, the real world is effectively hit with

productivity shocks that the monetary authority is always unaware of. On average it will get the level of potential right, but over the cycle it will be making errors and these errors will always be correlated with the evolution of the cycle in each draw.

This may not be the ideal approach. It might be preferable to have the monetary authority estimate potential output each period as new data becomes available within each simulation. In this way, the choice of policy rule would affect its estimate of potential output and thus the errors that it is making would be contingent on the policy rule followed. However, this approach would increase the time it takes to generate our results by a factor of 30 to 40. Because FPS is a nonlinear forward-looking model, it is solved using a forward-path-solution technique that is computationally intensive. Consequently, our current technology would not allow us to consider using the more ideal approach.<sup>16</sup>

**Figure 6**  
**Actual output, filter and smoother estimates of potential output**



It is worth noting that this analysis does not consider whether the HP filter is the “correct” unobserved components model to be using to estimate potential output. Example of literature examining this issue are Harvey and Jaeger (1993), Cogely and Nason (1995) and Guay and St-Amant (1996). As noted earlier, the HP filter is a particular restricted version of a more general unobserved components model and, consequently, this dimension of the issue should be thought of as parameter uncertainty rather than the filter uncertainty considered here.

<sup>16</sup> To generate the efficient frontier under forward-looking inflation targeting rules with uncertainty about potential output using our current technique takes one pentium dual processors with a 300 MHZ clock roughly 12 days of simulation time.

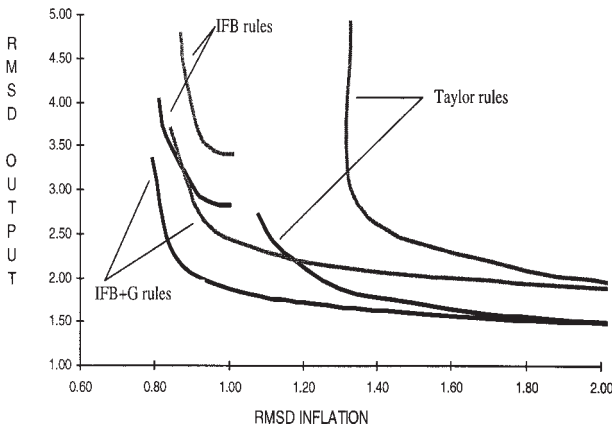


Even given these limitations, one can argue that this technique is providing an effective proxy for the type of errors that a monetary authority might make about the evolution of potential output. In figure 6, the evolution of real output for one draw under the base-case policy rule is graphed against the proxy for the monetary authority's current estimate of potential output (filter estimate) and the ex-post estimate of potential output (smoother estimate). When output is expanding rapidly, the monetary authority tends to overestimate potential output growth and when output growth is weak the monetary authority tends to underestimate potential output growth.

## 4.2 The implications of uncertainty

The stochastic experiment in section 3 is repeated for all three classes of policy rules under uncertainty about the evolution of potential output and the resulting efficient frontiers are traced out. The relative performance of the three classes of rules are graphed in figure 7. Under uncertainty, a similar story emerges to that under certainty. Taylor rules can achieve output variability that is not achievable under IFB rules; however, they cannot achieve similar inflation variability performance. IFB+G rules can achieve the low output variability of Taylor rules while achieving similar inflation performance to IFB rules.

**Figure 7**  
The implications of uncertainty for efficient frontiers



Not surprisingly, the minimum achievable combinations of inflation and output variability deteriorates for all three classes of rules under uncertainty about potential output. The largest relative deterioration in performance occurs for the Taylor rules. Where the most deterioration in performance occurs depends on where the Taylor rules lie in terms of “hawkishness” on inflation. The more severe the rule is on inflation, the more the performance deteriorates in terms of output variability. The less hawkish the rule is on inflation, the more the relative performance of inflation

variability decreases. This contrasts interestingly with the performance of IFB+G rules. Under these rules becoming more hawkish on inflation does not materially change the deterioration in terms of output variability, it simply *reduces* the relative deterioration in inflation variability. For IFB rules, virtually all of the deterioration shows up in an increase in output variability.

The relative shifts in the three classes of efficient rules to some extent reflects the nature of the rules that lie on the efficient frontier. The IFB rules that lie on the frontier are all fairly hawkish, with the magnitude of the weights being 5 or larger on the forward-looking inflation gap. However, the efficient frontiers under the other two classes of rules have weights on the inflation gap (forward-looking or contemporaneous) that range from 0.5 to 20. Consequently, these efficient frontiers shift back more in inflation terms than do the IFB rules.

Considering the change in the characteristics of efficient rules under uncertainty illustrates some interesting differences. For the Taylor rules that achieve the very lowest variability in inflation, the weights on inflation and the output gap actually increase relative to those under certainty about potential output. For efficient rules that achieve the lowest variability in output, no change occurs in their characteristics. On the other hand, the change in characteristics of IFB+G rules occurs in those that achieve the lowest variability in output. For these rules, the forward-looking horizon increases. Under forward-looking inflation targeting rules, the change in characteristics is small and occurs in those that achieve the lowest variability in output. For these rules, the weights on the inflation gap increase slightly under uncertainty.

Both the direction and the relatively minor magnitude of the changes in the characteristics of efficient rules under this dimension of uncertainty about potential output are rather different from the implications of uncertainty about potential output in Smets (1999) and uncertainty about the natural rate of unemployment in Weiland (1998). In Smets (1998), filter uncertainty associated with the unobserved components model considered reduced the degree of activism of optimal Taylor rules. The magnitudes of the coefficients on both the output gap and to a lesser extent the contemporaneous deviation of inflation from target in optimal Taylor rules declined relative to the case of no uncertainty. In Weiland (1998) uncertainty about the natural rate of unemployment also reduced the degree of activism of optimal policy rules.

In the case of Weiland (1998), the uncertainty about the natural rate of unemployment enters the optimisation problem in such a way that it parallels the standard Brainard (1967) characterisation of policy multiplier uncertainty and the results are consistent. In the case of Smets (1998) the characterisation of uncertainty more closely parallels that considered here and consequently the different results are slightly more difficult to reconcile. There are two potential sources for the difference. The first is related to the nature of the filter uncertainty that arises from the HP filter and the second compounds the first and is related to the asymmetric inflation process in FPS.

The error on potential output that arise from the HP filter uncertainty is in general correlated with the business cycle and has persistent serial correlation. Consequently, the monetary authority on average underestimates the degree to which inflation will be deviating from the target over the cycle. Consequently, responding less strongly implies inflationary disturbances get even more embedded in expectations and become more costly to unwind. This leads to the second source, the

asymmetric inflation process in FPS. Because excess demand leads to more inflationary pressure than an equivalent amount of excess supply leads to deflationary pressure, unwinding inflation shocks leads to permanent losses of output. In a stochastic world, output will on average be below its deterministic steady state (potential) and inflation will be above target.<sup>17</sup> The efficient frontiers presented here are calculated using RMSD from deterministic steady state and thus they penalise policy rules that lead to average outcomes that deviate from these levels. The less activist the policy rule, the greater will be these deviations.

It is worth noting the results obtained here are consistent with those in Isard and Laxton and Eliasson (1998). Here the authors examine the implications of uncertainty about the natural rate of unemployment in a model with a similar non-linear inflation process to that in FPS. The uncertainty about the natural rate arises from filter uncertainty from an unobserved components model and the resulting error exhibits similar serial correlation. The authors find that increasing the weight on the deviation of inflation from target in a Taylor rule reduces both inflation and output variability under this uncertainty.

As noted earlier, an important consideration is also the variability of nominal interest rates. If the set of rules considered is limited to those with instrument variability consistent with a non-negativity constraint the efficient frontiers are those traced out in figure 8. The dark dashed lines trace out the efficient frontiers under certainty and instrument constraints and the dark lines trace out the implications under uncertainty and instrument constraints. Two points are worth noting. The first is that the characteristics of rules that lie on the efficient frontier remain virtually unchanged for Taylor rules and IFB+G. Only the characteristics of IFB rules change under uncertainty with instrument constraints. Under these rules, the effect of uncertainty is still to slightly increase the weights on the inflation gap on those rules that achieve the lowest variability in output. However, the weights do not increase as much as they do when there is no constraint on instrument variability. The second point is that Taylor rules and FB+G rules are the most affected by the instrument constraint. Again their ability to reduce output variability relative to IFB rules becomes less pronounced. This point is illustrated in figure 9 which shows the impact of instrument constraints on the efficient frontiers under uncertainty about potential output.

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<sup>17</sup> For a more complete discussion of why this arises see Laxton, Rose and Tetlow (1994).

Figure 8  
The implications of uncertainty plus instrument constraints

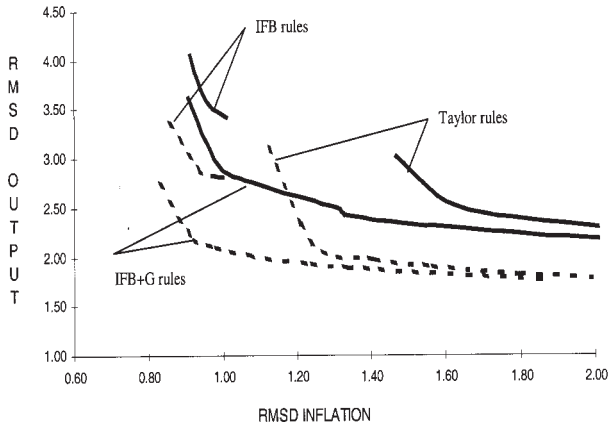
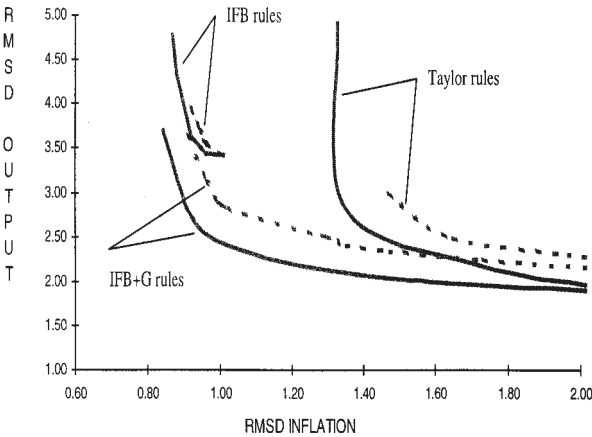


Figure 9  
The implications of instrument constraints under uncertainty



## 5.0 Summary and conclusions

In this paper the relative performance of three classes of policy rules is examined using stochastic simulations of the Reserve Bank of New Zealand's macroeconomic model, FPS. The resulting efficient frontiers achievable under these rules illustrate that Taylor rules can achieve lower output variability than IFB rules. However, to achieve the same inflation variability performance, the inflation gap entering a rule including the contemporaneous output gap needs to be forward looking (an IFB+G rule). Consequently, a policy rule containing features of both Taylor rules and IFB rules can achieve outcomes that are unambiguously better than either of the rules can achieve individually. Although reasonable constraints on instrument variability slightly reduce the output variability performance of rules that respond to the contemporaneous output gap, the qualitative story remains the same.

In response to the criticism that uncertainty will reduce the efficacy of IFB rules, the implications for these results, when the monetary authority is uncertain about the evolution of potential output, is also examined. A proxy for a monetary authority's typical error process is generated based on filter uncertainty related to the Hodrick-Prescott filter. The resulting error about potential output is correlated with the evolution of the business cycle in each of the 100 draws used for the stochastic experiment. The resulting efficient frontiers illustrate that the results under certainty are robust to the type of uncertainty examined. Further, under uncertainty, there are only very minor differences in the characteristics of rules that lie on the efficient frontier. Those differences that do arise suggest that policy should be more activist rather than less so in the face of this uncertainty. This highlights an important point for policy makers, different dimensions of uncertainty will have different implications for how policy should respond. The standard Brainard (1967) intuition that uncertainty implies cautions may not always apply.

Looking ahead, it would be worthwhile to examine both filter and parameter uncertainty within a unified framework derived from an unobserved components model that was fit specifically to the New Zealand data. This would yield more quantitative rather than merely qualitative advice on the design of efficient policy rules. Further it would consider the implications of both filter and parameter uncertainty. Additionally, imposing a non-negativity constraint within the simulations and searching over more response coefficients on the contemporaneous output gap that lie within the feasible range might yield more interesting results on the implication of uncertainty.

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## Appendix: Generating stochastic simulations

This appendix discusses how stochastic simulations were performed using the core structural model in the FPS. First, the VAR model of the New Zealand economy is outlined. Second, the method by which the impulse response functions (IRFs) from the VAR are mapped into a set of shocks to the core model equations, such that the model replicates the IRFs from the VAR is discussed. The methodology used to implement the shocks stochastically is then presented.

### A.1 The estimated VAR model

To capture the stochastic structure of shocks to the New Zealand macro-economy we estimated a six-variable VAR model. The following variables are included in the VAR:

- foreign demand ( $fd$ )
- terms of trade ( $tot$ )
- consumption plus investment ( $c + i$ )
- price level ( $cpi$ )
- real exchange rate ( $z$ )
- slope of the yield curve ( $rsf$ )

The foreign demand variable is measured as the total industrial production of the OECD. The terms of trade is calculated as the domestic price of exports divided by the price of imports. Shocks to the sum of consumption and investment are interpreted as the result of shocks in aggregate demand. The price index is measured as the consumer price index excluding interest rate effects and GST.<sup>18</sup> The real exchange rate is calculated using the domestic output deflator, the nominal trade weighted index and trade weighted foreign output deflators. Finally, the yield spread is measured as the 90-day rate minus the five year rate. The yield spread enters the VAR in levels and all of the other variables are in log levels.

The variables of the VAR and their associated shocks terms are intended to replicate the stochastic behaviour of macroeconomic disturbances hitting the New Zealand economy. There are, however, a number of omissions. Perhaps the most notable is shocks to the economy's productive capacity. Initially, an estimate of New Zealand's potential output was also included in the VAR. However, given the short length of the sample period there is insufficient stochastic information in the potential output series to produce sensible shock responses. Despite this omission, innovations in the economy's level of productive capacity will in part be captured by the shock terms of the other variables of the system. Stochastic innovations in the domestic price level, for example, can be partially attributed to temporary aggregate supply shocks.

In the reduced form system of equations foreign demand and the terms of trade are modelled as block exogenous on the assumption that New Zealand is a small open economy. Lags of the

<sup>18</sup> GST is a goods and services tax. This tax was initially implemented in 1986 at 10%. In 1989, GST was increased to 12.5%.

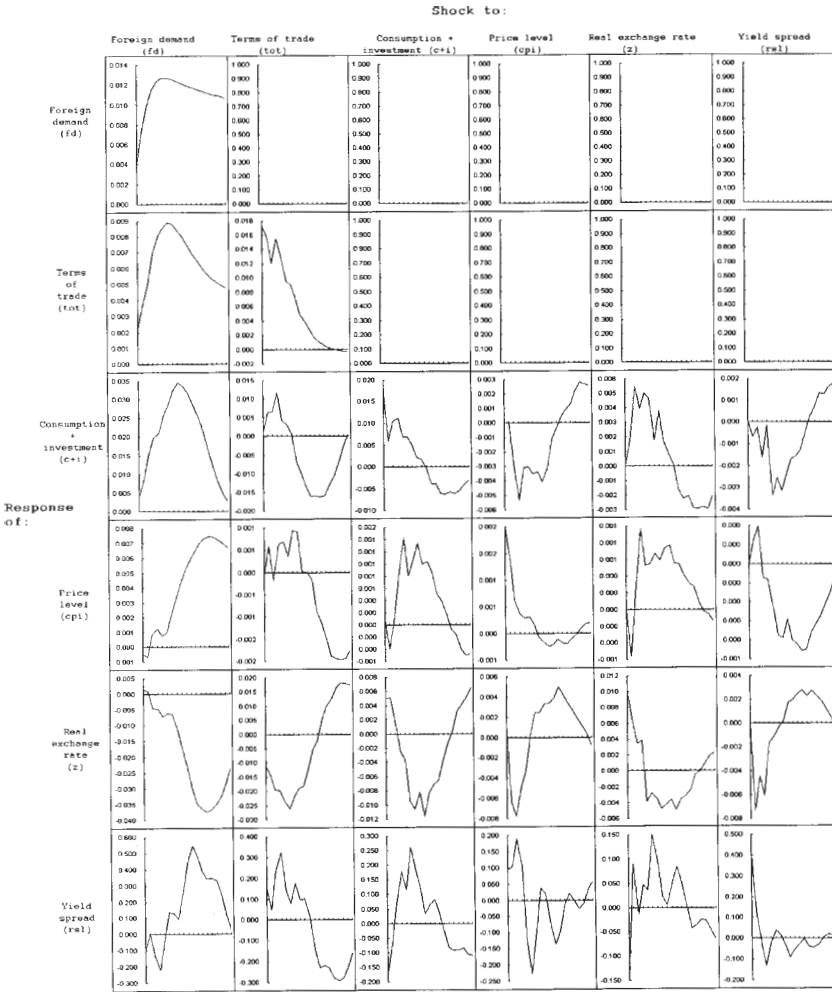
domestic variables do not, therefore, enter into the equations describing these variables. Foreign demand is assumed to be strictly exogenous in that it is only dependant on its own lags. The equation describing the terms of trade includes its own lags and lags of foreign demand. The equations describing the domestic variables and the real exchange rate are identical and contain lags of all the variables of the system. On the basis of modified likelihood ratio tests, the number of lags in the system is set at four. Ljung-Box  $Q$  statistics confirm the lack of serially correlated residuals at the 5% level of significance. The reduced form is estimated over the sample period 1985q2 to 1997q2 using the method of seemingly unrelated regressions.

To calculate impulse response functions we identify the moving-average representation of the VAR system by imposing a simple contemporaneous causal ordering. The structure of FPS implies an ordering of  $\{fd, tot, c + i, cpi, z, rs\}$ . Foreign demand and the terms of trade are placed causally prior to the domestic variables. This specification extends the assumption of block exogeneity of the foreign sector to the contemporaneous interaction between the variables of the system. In the domestic block,  $c + i$  and  $cpi$  adjust with a lag to shocks in the real exchange rate and monetary conditions. Finally, the monetary authority is assumed to set monetary policy on the basis of contemporaneous (and historical) information.

The impulse responses of the variables in the VAR to each of the six shocks are presented in figure 10. In all cases the magnitude of the shocks is equal to one standard deviation. The figure should be read vertically; each column shows the response of each variable to a particular shock.

In general, the IRFs accord well with the theory of small open economy macro-dynamics. Consider the effect of a one standard deviation shock to foreign demand. The terms of trade improves and the real exchange rate appreciates, consistent with increased demand for New Zealand exports. Aggregate demand, in the form of consumption plus investment, increases inducing a lagged increase in the price level. The monetary authority reacts to increased inflationary pressure by tightening monetary conditions, causing the yield spread to increase. Increased domestic interest rates exacerbates the appreciation of the real exchange rate. In response to a one standard deviation shock to  $c + i$ , foreign demand and the terms of trade remain unchanged given that they are exogenous. The price level increases after two periods, inducing a tightening in monetary conditions. After three quarters the real exchange rate appreciates.

Figure 10  
VAR impulse response functions



### A.2 Translating VAR impulse response functions into shocks to FPS

In the VAR system, an IRF is generated by applying a 1 standard deviation innovation to a variable. The effect of that impulse is seen on all variables in the VAR, subject to the causal ordering of the system and the estimated auto and cross correlations of the variables. Given an impulse, the resultant paths for macroeconomic variables in the VAR can be interpreted as deviations from control or equilibrium.

In the core model, each behavioural equation has an associated shock term. Deviations from control arising from an impulse to the VAR are added to the control levels of those behavioural variables in the core model that most closely match the VAR variables. The core model is then simulated with the behavioural variables concerned exogenous and shock terms on the behavioural equations endogenous. This effectively “backs out” the shocks to the core model that replicate the VAR impulse. This exercise is repeated for each IRF produced by the VAR system.<sup>19</sup>

The shocks necessary for the model to replicate the VAR are backed out only for the first four quarters and the policy reaction function in the model is switched off over this period. This is done so that the shock terms are independent of the response of monetary policy over the first year, and consequently independent of the specification of the policy reaction function. By construction, therefore, the methodology assumes that the VAR's IRFs are independent of the implicit policy reaction function in the VAR over the first year. Given the long lags between policy actions and real economy responses this is probably a reasonable assumption. Further, it assumes that the response of the policy instrument in the IRFs is the result of policy actions alone. This assumption may be a bit strong as the policy instrument may in fact be subject to other innovations in addition to monetary policy actions.

The shocks required to get FPS to replicate the IRFs are serially and cross correlated. To capture this in such a way that the stochastic simulations can be implemented by drawing random normal (0,1) numbers, the shock terms that appear in the behavioural equations in the model are re-written. A simple example is used below to illustrate how this works.

Example - creating single period shocks that replicate VAR IRFs

Suppose that there is only two variables used in the VAR system, X1 and X2, where an impulse to X1 does not effect X2 but an impulse to X2 effects itself and X1. The impulses to the system are mapped to the behavioural FPS variables  $x_1$  and  $x_2$  which have associated shock terms  $x_{1\_shk}$  and  $x_{2\_shk}$ .

Truncated after four quarters, the shocks paths required for the model to replicate the paths arising from the IRFs are:

1) Impulse to X1

$$x_{1\_shk} = \{a^{1_{1,1}}, a^{1_{1,2}}, a^{1_{1,3}}, a^{1_{1,4}}, 0, \dots, 0\}$$

$$x_{2\_shk} = \{0, \dots, 0\}$$

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<sup>19</sup> Two variations of this exercise were examined. In the first, the whole path for the impulses are added to the matching FPS behavioural variables and shock terms are solved for. In the second, the model is simulated quarter-by-quarter with only the contemporaneous effect of the impulse seen each quarter. This makes the problem for the monetary authority harder as the future impact of the impulses are not seen, but is probably more realistic as policy makers do not, in general, know what shocks are hitting the economy at any point in time let alone know the future impact of any shock. As such, this second variation was used in performing the stochastic simulations in this paper.

2) Impulse to X2

$$x_{1\_shk} = \{a^2_{1,1}, a^2_{1,2}, a^2_{1,3}, a^2_{1,4}, 0, \dots, 0\}$$

$$x_{2\_shk} = \{a^2_{2,1}, a^2_{2,2}, a^2_{2,3}, a^2_{2,4}, 0, \dots, 0\}$$

where  $a_{j,t}$  is the numerical solution for the value of the shock term at time  $t$ , given the effect the IRF  $i$  has on the behavioural variable  $j$ .

Let  $e_t$  be a single period random number at time  $t$ . If this random number equals one, then it will generate the shock path required to replicate the IRF with the shock structure coded in the behavioural equation as follows:

$$\begin{aligned} x_{1\_shk_t} &= a^1_{1,1} * e^1_t + a^1_{1,2} * e^1_{t-1} + a^1_{1,3} * e^1_{t-2} + a^1_{1,4} * e^1_{t-3} + a^2_{2,1} * e^2_t + a^2_{2,2} * e^2_{t-1} \\ &\quad + a^2_{2,3} * e^2_{t-2} + a^2_{2,4} * e^2_{t-3} \\ x_{2\_shk_t} &= 0 * e^1_t + 0 * e^1_{t-1} + 0 * e^1_{t-2} + 0 * e^1_{t-3} + a^2_{2,1} * e^2_t + a^2_{2,2} * e^2_{t-1} + a^2_{2,3} * e^2_{t-2} \\ &\quad + a^2_{2,4} * e^2_{t-3} \end{aligned}$$

Essentially then, the methodology implemented re-writes the shock terms in the behavioural equations to capture all the impulses in the VAR system. The shock paths required to replicate IRF<sub>1</sub> for one year will be generated when the random number  $e_t$  is takes the value one.

Extending the above example to replicate the VAR in this paper is relatively simple. There are five shock terms that are re-written rather than two. Any individual shock term  $j$  appearing in a behavioural equation is represented by:

$$1) \quad x\_shk_{jt} = \sum_{i=1}^5 \sum_{k=0}^3 \alpha^j_{j,k+1} e^j_{t-k}$$

### A.3 Generating stochastic simulations

It is convenient to write the full set of behavioural shocks as:

$$2) \quad \mathbf{X}_t = \mathbf{A}\mathbf{E}_t$$

where:

$\mathbf{X}_t$  is a vector of the shock terms in the behavioural equations at time  $t$

$\mathbf{A}$  is a matrix of the  $a_{j,t}$  coefficients

$\mathbf{E}_t$  is a vector of the  $e_t$  random variables that exist from time  $t-3$  to  $t$ . This can be de-composed into four sub-vectors  $\mathbf{e}_{t+i}$ , where each  $\mathbf{e}_{t+i}$  is a vector of the random numbers at time  $t-i$  only.

The stochastic simulations in this paper were generated using the following procedure. First, elements of the vector  $\mathbf{e}_t$  are drawn from a standard normal (0,1) distribution. Given this vector of random impulses a "shock model" solves for the shock vector  $\mathbf{X}_t$ . The FPS core model is then

simulated with this shock vector exogenous and all the behavioural variables endogenous. This counts as one “iteration” of the model. Typically, in the stochastic simulation experiments considered in this paper, a single “draw” consisted of simulating the model for 100 iterations, where in each iteration a new vector for  $\mathbf{X}_t$  is generated given the historical and contemporaneous stochastic iid impulses in  $\mathbf{E}_t$ . This exercise is repeated for 100 draws. Furthermore, the drawing of the iid random numbers are seeded so that for each set of 100 draws, an identical battery of shocks are generated.