Monetary Policy in a Changing Economy:

Indicators, Rules, and the Shift Towards Intangible Output

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Abstract

This paper considers the effects of the trend towards knowledge-based production on indicators that are used in forming monetary policy and the resulting implications for the conduct of monetary policy. Two specific questions are addressed. First, are recent changes in the NAIRU in the U.S. and in some other developed countries related to the worldwide trend towards knowledge-based production? Second, what are the implications of these changes for the conduct of monetary policy? The empirical analysis suggests that this trend is not a proximate or primary cause for the shifts in the NAIRU. However, there is evidence that the NAIRU and other key macroeconomic relations have shifted, and this introduces important additional uncertainties that must be confronted by monetary policymakers. The paper therefore turns to a quantitative analysis of monetary policy rules that are robust to such uncertainty. This investigation is undertaken in a small macroeconomic model of the U.S. economy, and the uncertainty is modeled as arising from parameters that evolve over time according to random walks. The robust rules that emerge suggest that, for some types of uncertainty, a monetary authority facing uncertainty about the structure of the economy should consider policies that are somewhat more aggressive than might be indicated by simple point estimates of their models.

Key words: Knowledge-based economy, Time varying NAIRU, Taylor rule

JEL classification: C50, E52, O30

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1. Introduction

The trend towards production in which knowledge and intellectual activity plays an increasingly important role, and in which output is often intangible, holds the possibility of changing the speed and nature of many aspects of microeconomic activity. These range from having an increasingly decentralized workforce, to increasing consumer and worker access to information, to reducing transactions costs in markets. Such broad changes arguably could alter the relationship between economic indicators and overall economic activity, both because these shifts exacerbate the challenges of measuring productivity and inflation, and because these shifts introduce structural changes that could affect timing and correlations between macroeconomic time series.

This paper considers the effects of the trend towards knowledge-based production on indicators that are used in forming monetary policy and the resulting implications for the conduct of monetary policy. At a general level, monetary policy is conducted using many indicators, formal and informal. Some of these indicators measure demand pressure; most prominently, these include the gap between the unemployment rate and the natural rate of unemployment, as measured by the non-accelerating inflation rate of unemployment (the NAIRU), and the GDP gap (the gap between real GDP and potential GDP). Other indicators focus on supply shocks, such as price inflation for imported commodities. One would expect that, to a greater or lesser degree, the relation of all these indicators to economic activity, and thus their value to monetary policy authorities, would change with underlying shifts in the structure of the economy.

In the United States, the recent low rates of unemployment has put one of these indicators, the gap between the unemployment rate and the NAIRU, at the center of policy discussions. This

paper therefore addresses two questions. First, are recent changes in the NAIRU in the U.S. and in some other developed economies related to the worldwide trend towards knowledge-based production? Second, what are the implications of these changes, and of uncertainty about an evolving economy more generally, for the conduct of monetary policy? These questions are addressed in three steps.

First, evidence on the NAIRU in the major economies in North America and Europe is examined. Several studies, including Staiger, Stock and Watson (1997a,b), Gordon (1997), and the Council of Economic Advisors (1998), have concluded that there is evidence that the NAIRU has recently fallen in the United States. The analysis here follows these papers and estimates time varying NAIRUs by specifying the NAIRU as an unobserved stochastic process that is inferred from a Phillips-type relation. Some technical innovations, described in section 2, are used to estimate new quarterly time-varying NAIRU series for the U.S. Formal estimation of the NAIRU for other countries is not undertaken. However, informal evidence on trends in the natural rate of unemployment is discussed for Canada and the major European economies.

Second, the relationship between these time varying NAIRUs and measures of knowledge-based production is examined empirically. This is difficult because of the paucity of time series data documenting this shift. However, several proxies are suggested for the U.S. (specifically, shifts in the shares of employment and income of various service sectors and a time series on the returns to education) that permit some empirical analysis. While there is some evidence of a link between changes in the NAIRU in the U.S. and these proxies for knowledge-based production, the weight of the evidence is that the shift towards knowledge-based production does not appear to be a proximate or primary cause of changes in the NAIRU and in particular of the declines in the NAIRU over the 1990s.

Finally, implications are drawn for the conduct of monetary policy. The evidence is consistent with the view that both the relation between the unemployment rate and inflation and the relation between interest rates and the unemployment rate have evolved over the past several decades, although it is difficult to pinpoint the source of these changes. This raises the broader question of how to conduct monetary policy when the economy is evolving but the direction of that evolution is difficult to predict. To make the discussion concrete, this question is addressed using a modification of a model developed by Rudebusch and Svensson (1998) to study monetary policy rules. The results are surprising. In the presence of evolving parameters, and thus of uncertainty about the current values of the parameters, robust policy rules tend to be somewhat more aggressive than they would be were the parameters constant and known. In this model, at least, taking an aggressive policy stand guards against the possibility that policy is less effective than one would think based on the point estimates of the model.

2. Time-Varying Estimates of the NAIRU: Methodology

The definition of the NAIRU as the rate of unemployment that leads to a constant rate of price inflation provides a concrete framework in which the NAIRU can be estimated econometrically. This framework, due to Gordon (1982), is based on a Phillips-type relation in which changes in rates of inflation are determined by the unemployment rate, inertial effects (lagged changes in inflation), and supply shocks or other special factors. This framework constitutes the standard method for estimation of the NAIRU, cf. Congressional Budget Office (1994) and Fuhrer (1995). Specifically, the NAIRU is implicitly defined by the time series regression,

(1) $$\Delta \pi_t = \beta(L)(u_{t-1} - \bar{u}_{t-1}) + \delta(L)\Delta \pi_{t-1} + \gamma(L)X_t + \epsilon_t$$

where π_t is the rate of inflation, u_t is the unemployment rate, X_t is a vector of supply shock variables, L is the lag operator, $\bar{u}_t$ is the NAIRU at date t, and ϵ_t is a serially uncorrelated disturbance with mean zero and variance σ_ϵ^2. It is assumed in this literature and here that, after controlling suitably for supply shocks, ϵ_t is uncorrelated with the regressors. One justification for this is viewing (1) as a reduced form relation with in which the unemployment gap, $u_t - \bar{u}_t$, is predetermined but not strictly exogenous.

In the standard formulation, the NAIRU is assumed to be constant, that is, $\bar{u}_t = \bar{u}$. However, to examine the possibility that the NAIRU has changed over time and that these changes are related to knowledge-based production, this framework has been modified to include a time varying NAIRU. Following King, Stock and Watson (1995), Staiger Stock and Watson (1997a) and Gordon (1997), NAIRU is modeled an unobserved variable that follows a random walk:

(2) $$\bar{u}_t = \bar{u}_{t-1} + \eta_t, \; E\eta_t = 0, \; \text{var}(\eta_t) = \tau^2$$

where the disturbance η_t is serially uncorrelated and is uncorrelated with ϵ_t. When $\tau^2 = 0$, the NAIRU is constant; positive values of τ^2 permit movements in the NAIRU.

Estimation of the parameters of (1) and (2) presents some technical difficulties, and the approach adopted here differs from that previously used in the literature in two main ways. The first difference concerns parameter estimation. The model as written constitutes a state space model that is linear in variables but nonlinear in the parameters, with (1) being the measurement

equation and (2) the state equation. In principle the fixed parameters of the model (β(L), δ(L), γ(L), τ^2, σ_ϵ^2) can be jointly estimated by maximum likelihood in which the nonlinear restrictions across the parameters are imposed. The main difficulty with this approach, however, is that when the true value of τ^2 is small, the maximum likelihood estimator suffers from considerable finite-sample bias. This bias is related to the so-called "pile-up" problem in the estimation of a moving average coefficient when the true moving average root is nearly unity (see Stock (1994) for a discussion of the MA unit root case), and a similar pile-up problem exists here in which the MLE takes on the value $\hat{\tau}^2=0$ with high probability even when the true value of τ^2 is positive. Thus Staiger, Stock and Watson (1997b) and Gordon (1997) imposed values of τ^2 rather than estimating τ^2.

Here, I take advantage of recent theoretical developments in Stock and Watson (1998) to construct median unbiased estimates of τ^2 and confidence intervals for τ^2. These are then used to guide subsequent estimation. The method in Stock and Watson (1998) entails constructing confidence intervals for τ^2 by inverting certain tests for parameter stability using the method of confidence belts. They show that, asymptotically, confidence intervals thus constructed have the correct coverage rate under the nesting $\tau=O(1/T)$ (this is the neighborhood in which these tests have nontrivial asymptotic power). Because an equal-tailed confidence interval with 0% coverage is a median-unbiased estimator of τ (and thus of τ^2), this method provides both interval and point estimates.

This procedure can be implemented using a variety of break tests. The specific break test used here is the Wald statistic version of the Quandt (1960) likelihood ratio (QLR) test. This is the maximal value of the Wald regression test of no change in the regression coefficients (or a subset thereof), over a range $T_1,...,T_2$, where T_1 and T_2 are chosen to exclude the inital and final

15% of the observations. At the risk of some confusion, this will be referred to below as the QLR statistic even though it is computed in Wald form. Monte Carlo results and theory show that this maximal Wald statistic behaves very similarly to the Andrews-Ploberger (1994) test statistic, and has somewhat better size and power properties than the mean Wald statistic, see Stock and Watson (1996, 1998). Results were also computed for the Andrews-Ploberger (1994) and mean Wald statistic, and the results were similar to those obtained using the QLR statistic.

The second technical innovation involves a simpler strategy for the estimation of the remaining fixed parameters, $(\beta(L), \delta(L), \gamma(L), \tau^2)$. Given an estimate of τ^2, these parameters can be estimated by maximum likelihood using the Kalman filter. However, this is computationally cumbersome and the asymptotic theory in Stock and Watson (1998) provides a simpler approach. When $\tau = 0(1/T)$, (1) can be rewritten,

$$(3) \qquad \Delta\pi_t = \mu_t + \beta(L)u_{t-1} + \delta(L)\Delta\pi_{t-1} + \gamma(L)X_t + \tilde{\epsilon}_t,$$

where $\tilde{\epsilon}_t = \epsilon_t + O_p(1/T)$ and $\mu_t = \beta(1)\bar{u}_{t-1}$, so $\mu_t = \mu_{t-1} + \tilde{\eta}_t$, where $\tilde{\eta}_t = \beta(1)\eta_t$. Stock and Watson (1998) showed that, if $\delta(L) = 0$, then $\beta(L)$, $\gamma(L)$ and σ_ϵ^2 are efficiently estimated by ordinary least squares regression of $\Delta\pi_t$ on a constant and u_{t-1}, $\Delta\pi_{t-1}$, X_t, and their lags as called for in (1). It can further be shown that, for $\delta(L) \neq 0$, the least squares estimates of $\delta(L)$, $\beta(L)$, $\gamma(L)$ and σ_ϵ^2 are $T^{1/2}$-consistent. Based on this result, these parameters are here estimated by OLS.

Given these parameter estimates, $\bar{u}_t$ is estimated using the Kalman smoother in the linear state space model (2) and (3). Estimated signal extraction variances for $\bar{u}_t$ are computed using standard Kalman smoother formula. Note that these variances incorporate only uncertainty about $\bar{u}_t$ given the data and the parameters, and do not incorporate uncertainty about the parameters.

3. Time-Varying Estimates of the NAIRU

Results for the United States

Time-varying NAIRU specifications for the United States were estimated using quarterly data from 1961:1 to 1997:3, with earlier observations used for initial conditions. Inflation is measured by the annualized growth rate of the consumer price index (CPI). The supply shock variables are those used in Staiger, Stock and Watson (1997a,b), specifically Gordon's (1982) variable representing the imposition and elimination of the Nixon wage and price controls (entered contemporaneously) and a variable measuring the log of the ratio of the food and energy prices to the CPI. Five measures of the unemployment rate are used: the total civilian unemployment rate, aged 16 and over; the unemployment rate for married men with a spouse present; the unemployment rate of males, ages 25-54; the unemployment rate for males, ages 35-44; and Shimer's (1998) demographically adjusted unemployment rate. Shimer's adjustments correct for the changing demographics of the U.S. labor force and thus help to control for the implied shifts in labor force attachment (and the associated changes in the NAIRU) as the baby boom ages. Time varying NAIRUs were also estimated for other inflation measures (the chained GDP deflator, the chained personal consumption expenditure deflator, and the CPI excluding food and energy). Although the precision of the estimates of the NAIRU depends appreciably on which inflation series is used, the point estimates do not. Because the focus of this part of the paper is on understanding the relation between changes in the NAIRU and knowledge-based production, this means that little is lost by restricting attention to results based on the CPI.

Estimation and testing results are summarized in Table 1. Consistent with other results in the literature, the formal statistical evidence that the U.S. NAIRU has changed over time is mixed.

This is mainly a consequence of the imprecision with which the NAIRU is estimated. While the NAIRU might have changed over this sample, the standard framework for its estimation provides such imprecise estimates that it is difficult to distinguish statistically significant movements in the NAIRU. Similarly, the median unbiased estimates of τ are all small, in fact zero for three of the five unemployment rate series. At the same time, these results are consistent with the NAIRU exhibiting moderately large movements; the 90% confidence intervals contain values of τ up to approximately 0.10. This upper end corresponds to quarterly standard deviations of the movements in τ of approximately 0.1 percentage points, which in turn corresponds to a standard devation of decadal changes in the NAIRU of 0.6 percentage points.

Because using the small or zero point estimates of τ would result in NAIRUs that are constant or essentially so, for the purposes of this paper it is of greater interest to maintain the possibility that the NAIRU might have been changing over time and to extract the associated time varying NAIRUs. We therefore adopt the value $\tau=0.1$, which approximately corresponds to the upper end of the 90% confidence intervals for τ in table 1.

Estimated time varying NAIRUs (based on $\tau=0.1$) for three of the five unemployment rate series, extracted using the Kalman smoother, along with one standard deviation signal extraction error bands and the associated unemployment rate, are plotted in figures 1-3. Although the levels of the NAIRU depend on the unemployment rate series, the general time series pattern of the time varying NAIRUs does not. All the NAIRUs increase over the 1960s, peak around 1980, and show a marked decline during the 1990s. All of the NAIRUs also have large signal extraction errors, so that most of the actual values of the unemployment rate fall within a single standard deviation band.

Evolution of the unemployment rate in Canada and Europe

It would be of interest to have reliable estimates of time-varying NAIRUs for other G7 countries, since these could provide further insights into the relationship between information technology and the evolution of the NAIRU. However, there are several impediments to obtaining such estimates. Comparably defined data are not available across all these countries at a quarterly level for the long spans needed to estimate the coefficients accurately. Each country has, to a certain extent, its own unique set of supply shocks and institutional histories, and proper estimation of the NAIRU requires proper specification of these shocks and institutional nuances. Most importantly, some question whether the Phillips curve, as discussed so far, is appropriate for all the G7 countries. Certainly the experience of persistently high unemployment rates in the 1980s and 1990s in some European countries suggests that the time varying component of any NAIRU for those countries would need to be large. For these reasons, formal estimates of the NAIRU are not presented here for other G7 countries. Rather, some informal evidence is provided on trends in the natural rates of unemployment for these countries.

Table 2 contains evidence on the recent behavior of the rates of inflation and unemployment in the G7 countries, excluding Japan. (Japan is omitted because the slowdown and dropping rates of inflation of the 1990s makes historical comparisons difficult.) During the 1990s, each of these countries experience periods of approximately constant rates of inflation; these periods, and the associated changes in the annual rate of inflation, are listed in the first two numerical columns of the table. Because the rate of inflation was approximately constant over this multiyear period, the average unemployment rate over this period provides a crude estimate of the NAIRU in these countries (note however that this estimate does not control for supply shocks). Evidently, the NAIRUs for these countries vary considerably, with Canada, France, Italy and the UK having the highest estimates, and Germany and the U.S. the lowest. Comparison with the fifteen year

average unemployment rate over 1960-1974 suggests that for all these countries except the U.S., the NAIRU has risen substantially. Of course, this corresponds to the so-called problem of hysterisis in European unemployment rates. European unemployment rates have generally remained high for the past ten years, so this suggests that the NAIRU for France, Italy, and the UK has remained approximately constant over the past decade, while the Canadian NAIRU arguably has risen over the past ten years. Historical comparisons for Germany are less appropriate because of German unification.

With these estimates of time varying NAIRUs in hand, I now turn to the question of whether variations in the NAIRU are related to shifts in production towards knowledge-based and intangible output.

4. Are the changes in the NAIRU related to shifts toward intangible output?

Many explanations have been put forth for the trends in the NAIRUs evident in figures 1-3, especially the decline in the U.S. NAIRU during the 1990s. Some of these explanations involve increasing internationalization of product markets. According to this argument, firms face additional foreign competition, which leads to price restraint, so that prices do not increase as quickly when demand increases. Other explanations focus on labor markets. Because firms are increasingly mobile, according to this view workers fear that the firm will move production overseas if the workers aggressively press wage demands. Other explanations focus on demographics: as the baby boom ages, an increasing share of the workforce has higher job attachment, so all else equal the natural rate of unemployment will rise.

Another set of explanations involves technology and the shift towards knowledge-based production. Employment arrangements at knowledge-based firms seem to differ from those in traditional manufacturing, with greater turnover, possibly reflecting a greater importance of general human capital rather than firm specific human capital. To the extent that general human capital is increasingly important, training costs are reduced and search times could be shorter. Additionally, to the extent that production can be based on telecommuting rather than physical presence at the worksite, then the range of employment opportunities for unemployed workers in knowledge-based industries is increased (the transaction cost of taking a new job at a distant location is decreased). At the same time, this results in a larger pool of potential workers, so local labor supply restrictions are less binding which could serve to moderate wage increases. Finally, the amount of employment through temporary employment agencies has been increasing, at least in the United States, and improved information technology arguably facilitates job matching through these agencies. These considerations all suggest that shifts towards knowledge based production could reduce the natural rate of unemployment, which would be reflected in a decline in the NAIRU.

In this section, I focus on the final set of these explanations, the link between changes in the NAIRU and knowledge-based production. Because many aspects of knowledge-based production are new, only a limited amount of long time series data is available for this purpose. I therefore focus on two sets of proxies for knowledge-based production in the United States. The first set focuses on the rising importance of the service sector, in which much knowledge-based output is produced, and in particular on relatively skill-intensive service sectors. In particular, four proxies are examined: the share of total income produced in the service sector; the share of total employment in the service sector; the share of total employment in business services; and the share of total employment in finance, insurance and real estate.

The second measure is annual time series data on the returns to an additional year of education. The datum for a given year is the coefficient on years of education in an ordinary least squares regression of log wages on years of education and a standard list of socioeconomic control variables, estimated using the March Current Population Survey (these regressions contain between 24,000 and 120,000 observations, depending on the year). Because of data availability, this series starts in 1979, and because of a change in the survey measurement of the years of education in 1992, it ends in 1991. This series was taken from Abdul-Hadi (1997).

These series are plotted in figures 4-8. Also plotted in these graphs are adjusted time-varying NAIRUs for the five unemployment rate series for the U.S. To facilitate comparisons, these NAIRUs have been adjusted (rescaled and shifted) so that they are on the same basis as the NAIRU for the total unemployment rate; the parameters for the rescaling and shifting were taken from a regression of the particular unemployment rate, for example the married male unemployment rate, on the total unemployment rate.

It is evident from inspection of figures 4-8 that the five proxies for knowledge-based production and the time-varying NAIRUs have different trending properties. Generally speaking, these proxies all increase, whereas the NAIRUs increased in the 1970s and declined in the late 1980s and early 1990s. In terms of overall trends, the sharpest increases in the returns to education and in the importance of services in the economy have similar timing to the recent decline in the NAIRU. However, all these proxies were increasing for a considerable length of time prior to the recent declines. Although data on computer usage itself is not analyzed, the same trending features presumably would be found there, with the trend towards computerization occuring over many years and the decline in the NAIRU being a more recent phenomenon.

Formal statistical analysis of these relations is challenging because of the slowly moving trends in these series and the fact that the TV NAIRU is itself an estimated series. Nonetheless, it is useful to look at some cross-correlations, which are presented in table 3 for the services shares (no such results are presented for the returns to education because there are only 13 observations on that series). Changes in the shares of services (except for employment in finance, insurance and real estate) are negatively correlated with future declines in the NAIRU, although in many cases these correlations are not statistically significant.

Information that is arguably more useful is obtained by asking whether changes in the shares of services helps to predict changes in the NAIRU, given past changes in the NAIRU. This can be examined by Granger causality tests, p-values of which are reported in table 3. Two of the four measures of shares of services predict changes in the NAIRU at the 10% significance level, one of which (the employment share of business services) is significant at the 5% level.

Finally, it is useful to contrast these trends to the evidence on international trends in the NAIRU. The trend toward knowledge-based production has been present in all developed economies, so one would expect it to have a similar effect on the evolution of their NAIRUs. However, the recent behavior of the natural rate of unemployment differs sharply across G7 countries. For continential Europe, the NAIRU increased sharply during the 1970s and 1980s, and there is no sign of a decline in the 1990s. The natural rate also seems to have been approximately flat over the past ten years in the United Kingdom. However, the Canadian experience is similar to the United States. Thus, an attribution of these trends to shifts toward an information technology would need to explain why this shift causes an increase in the NAIRU in Europe but a drop in the NAIRU in North America.

Overall, these results provide a mixed view of the link between increased knowledge-based production and changes in the NAIRU. In terms of timing, the declines in the NAIRU in the U.S. are recent, but the trend towards increasing importance of services, the increasing returns to education, and increasing knowledge-based production has been with us for at least two decades. Moveover, different developed countries have different trends in the natural rate, yet if increasing knowledge-based production is an important source of these changes one would expect to see similar behavior of NAIRUs internationally. An examination of shorter run links for the U.S. (table 3) shows that increases in the share of services tend to be associated with future drops in the NAIRU. However, the ability of these changes to predict changes in the NAIRU is limited to one or two series. In summary, there is evidence that the NAIRU has been changing in G7 countries, but the evidence examined here suggests that these changes are not primarily driven by the trend towards knowledge-based production.

Before concluding this section, I briefly turn to another of the proposed explanations for the recent decline in the NAIRU in the U.S., the aging of the workforce (Shimer [1998]). According to this argument, the natural rate of total unemployment would decline as workers in the baby boom age, because older workers have greater labor force attachment. It is true that the NAIRU based on the prime-aged male unemployment rate, for example, is lower than that for the overall workforce, and varies less than the NAIRU for total unemployment. However, the time-varying NAIRU for married males, males ages 25-54, males ages 35-44, and the demographically adjusted unemployment rate is qualitatively similar to the NAIRU for overall unemployment. Once these five estimated time varying NAIRUs are placed on the the same scale by regression adjustment, as is done in figures 4-8, they are similar indeed, and in particular all show a decline in the NAIRU in the late 1990s. This graphical look at the data suggests that demographic changes, while

important for many aspects of the macroeconomy and labor markets, play a minor role in the historical evolution of the NAIRU in the U.S.

5. Monetary Policy in the Presence of Model Instability

The evidence in the previous sections suggests that the NAIRU has changed over time in the G7 countries. This section turns to the question of the conduct of monetary policy in the presence of the uncertainty that is caused by such changes.

The topic of policy rules under uncertainty has received considerable study. On a formal level, this literature typically has focused on the problem of optimal control when the model parameters are unknown and when the decisionmaker is able to place a prior distribution over the unknown parameters. In a static context with linear models and quadratic loss, the resulting optimal policy rules are based on parameter values that are shrunk towards zero (Brainard [1967]). In a dynamic context, optimal dynamic policy typically involves some deliberate experimentation to learn about the parameter values, see Wieland (1996, 1997).

A drawback of this standard decision theoretic approach is that it requires policymakers to specify prior distributions over parameters. Given the complexity of the models actually used in the conduct of monetary policy, this is entirely unrealistic. This section therefore pursues an approach which does not require priors and in this sense is better suited to generalization to actual policymaking problems. The specific approach here is adopted from the literature on robust control, and is based on finding minimax rules, that is, policy rules that minimize the maximum risk over some specified subset of the parameter space.

- 15 -

To illustrate this approach, and the importance of parameter evolution more generally, I consider a simple two-equation model taken from Rudebusch and Svensson (1998), estimated on quarterly U.S. data. Their model consists of a Phillips-type equation linking inflation to a demand measure, and of an equation linking the demand measure to monetary policy as measured by the ex-post real federal funds rate. Three modifications of their model are made here. First, their demand measure is the output gap; to be consistent with the emphasis so far on the NAIRU, this is replaced here by the unemployment gap (the unemployment rate less the NAIRU). Second, their Phillips equation does not control for any supply shocks; for consistency with the previous sections, I include the two supply shock measures that were used above to estimate the NAIRU models for the U.S. (the Nixon price controls and the relative price of food and energy). Third, I allow for some of the key parameters to vary over time.

The modified Rudebusch-Svensson model is,

(4) $\qquad \Delta\pi_t = \alpha_\pi(L)\Delta\pi_{t-1} + \alpha_{y,t}(u_t - \bar{u}_t) + \gamma' X_t + \epsilon_{1t}$

(5) $\qquad u_t = \mu_t + \beta_u(L)u_{t-1} - \beta_{r,t}(\bar{i}_{t-1} - \bar{\pi}_{t-1}) + \epsilon_{2t}$

where $\alpha_\pi(L)$ is a third order lag polynomial, $\beta_u(L)$ is second order, $\bar{i}_t$ is the four-quarter moving average of the Federal Funds rate (so $\bar{i}_t = (i_t + i_{t-1} + i_{t-2} + i_{t-3})/4$), $\bar{\pi}_t$ is the four quarter moving average of inflation, and X_t are the supply shock proxy variables. Rudebusch and Svensson (1998) provide motivation for studying this model. For the purposes here it suffices to view these as two reduced-form equations that describe the evolution of unemployment and inflation.

Following Rudebusch and Svensson, the policymaker is assumed to have quadratic loss (L_t) involving annual average inflation, the unemployment gap, and changes in the nominal interest rate:

$$(6) \qquad L_t = \bar{\pi}_t^2 + a_u(u_t - \bar{u}_t)^2 + a_i(i_t - i_{t-1})^2.$$

The loss function parameters are set to $a_u = 4$ and $a_i = 8$.

The model (4) and (5) involves two sets of time-varying parameters, an intercept drift ($\bar{u}_t$ and μ_t) and time variation in the slope coefficients $\alpha_{y,t}$ and $\beta_{r,t}$. Under quadratic loss, the optimal rule given all the slope coefficients does not involve the intecepts. I therefore focus on the time varying slope coefficients, which are modeled as,

$$(7a) \qquad \alpha_{y,t} = \alpha_{y,t-1} + \eta_{1,t}$$
$$(7b) \qquad \beta_{r,t} = \beta_{r,t-1} + \eta_{2,t}$$

where $\eta_t = (\eta_{1,t}\ \eta_{2,t})'$ is serially uncorrelated, uncorrelated with ϵ_t, and has covariance matrix Σ.

The econometric methodology described in section 2 to estimate the time-varying NAIRU models was used to used to estimate the complete model (4), (5) and (7). Estimation was performed equation by equation using U.S. quarterly data from 1961:1 to 1997:3, with earlier observations for initial conditions. Time varying parameters were estimated for the four intercept and slope coefficients. For the optimal control calculations below, to focus attention on the role of evolution of the two slope coefficients in (7), all other coefficients are treated as constant and known.

To discuss optimal policy, one must specify a class of policy rules. One approach is to derive model-specific optimal policies in the standard way specified in optimal control theory. For the purposes of this illustration, however, the results are more transparent if attention is restricted to a simple class of policy rules. There is in fact a large literature on simple rules for monetary policy, see the papers in Taylor (1998) for a summary. Again, I follow Rudebusch and Svensson and consider policy within the context of a parameterized rule of the type considered by Taylor (1993):

(8) $$i_t = g_\pi \bar{\pi}_{t-1} - g_u(u_{t-1} - \bar{u}_t)$$

The original Taylor rule (Taylor [1993]) is expressed not in terms of the unemployment gap but in terms of the output gap, and is $i_t = 1.5\bar{\pi}_{t-1} + 0.5 y_t^{gap}$, where y_t^{gap} is the relative gap between actual GDP and potential GDP in percentage points. This rule can be converted to one based on the unemployment gap using Okun's law. With an Okun's law coefficient of 2.5, the coefficient on the output gap corresponds to a coefficient on the unemployment gap of 1.25. It will be convenient to refer to this rule, $i_t = 1.5\bar{\pi}_{t-1} - 1.25(u_{t-1} - \bar{u}_t)$, as the unemployment-based Taylor rule.

Based on these estimated parameters and loss functions, two calculations were performed. The first provides a calibration of whether the estimated time variation is signficant from an economic perspective. This calculation addresses the counterfactual question, suppose the estimated time varying slope coefficients, along with the other model coefficients, had in fact been known historically. What would have been the time path of the optimal Taylor-type rule coefficients?

The answer to this question is given by the two time series of coefficients, g_π and g_u, plotted in figure 9. Although the optimal (counterfactual) coefficient on inflation is relatively constant, the coefficient on unemployment varies considerably over this period. At the end of the sample, the coefficient on inflation is 2.3 and the coefficient on the unemployment gap is 0.8. Thus, for these coefficients, the optimal central bank rule reacts somewhat more strongly to inflation than under the Taylor rule (g_π=2.3 vs. 1.5 for the Taylor rule) but somewhat less strongly to the unemployment gap than under the Taylor rule (g_u=0.8 vs. 1.25 for the unemployment-based Taylor rule). While not identical, these coefficients are broadly in keeping with those of the Taylor rule. According to these calculations, the optimal counterfactual rule would react less to an increase in unemployment now than in the early 1980s.

Of course, in real time the parameters are unknown, both because of econometric (sampling) uncertainty and because the model changes over time. What is the optimal policy for a central bank in this model, faced with such uncertainty? Here, I focus on the second of these sources of uncertainty, which reflects the recognition that the economy is changing over time but the nature of that change is incompletely understood.

To compute the optimal control rule under this uncertainty, suppose that the central bank is concerned about minimizing loss in a worst-case scenario, that is, that the central bank is interested in following a minimax policy. This policy will be a robust control rule in the sense that it guards against worst-case outcomes. To calculate this rule, it is necessary to have a measure of the uncertainty associated with the time evolution of the model. This is provided by the Kalman filter estimate of the time varying coefficients and of the signal extraction error covariance matrix. For specificity, these are computed for the final quarter in the sample, 1997:3, and the minimax rule is computed by considering parameters that fall in a one standard deviation

confidence elipse around the Kalman smoother point estimate of the time-varying slope

coefficients for 1997:3.

The resulting minimax robust policy for 1997:3 has coefficients of $g_\pi = 3.4$ and $g_u = 1.5$. These

coefficients are both larger than the optimal coefficients for 1997:3 in the absence of uncertainty,

portrayed in figure 9. The coefficient on unemployment is approximately the same as the

corresponding coefficient in the unemployment-based Taylor rule. However, the coefficient on

inflation in the robust rule is more than twice the Taylor rule coefficient on inflation.

Evidently, the minimax robust rule is more aggresive than the rule that ignores parameter

uncertainty, in the sense that the reaction to an increase in the unemployment rate or in inflation

is more vigorous. This might seem initially surprising from the perspective of Brainard-type

calculations, in which uncertainty induces less vigorous responses. Under the minimax policy,

however, the policymaker is guarding against parameter values that include ones in which policy

has very little effect. In that circumstance, an aggressive response is called for; if this induces

overshooting, as it will if the response to policy is larger than for the worst-case parameters, then

this overshooting can be subsequently counteracted. On net, the disadvantages of a too-vigorous

policy in the case that policy is effective are outweighed by the advantages of an aggressive

response in the case that it is not.

6. Discussion and Conclusions

There are many reasons for the evolution of the NAIRU in developed economies over the past

four decades. Recently, a possible source of this evolution is the shift to an information economy

and the growing importance of computers. The analysis of section 4, which uses shares of employment and the return to education to proxy for the trend towards an information economy, suggests that this trend is not a proximate or primary cause of the shifts in the NAIRU that have been seen in the past few years. It is difficult to obtain long time series that accurately measure the trends towards knowledge-based production, and using different proxies might yield different conclusions. What the foregoing analysis indicates, however, is that because many changes in the economy affect these series, because the trends are long-term, and because these series are in any event measured with considerable noise, it is difficult to isolate statistically the role of any one of these factors.

The fact that the source of these shifts is not readily apparent underscores the importance of examining monetary policy that is robust to changes in the underlying economy, whatever their source. The main finding from section 5 was that the amount of parameter variation estimated in a small macroeconomic model for the U.S. is economically important, and that different policies result when thus time variation is taken into account. The robust rules that emerge suggest that a monetary authority facing uncertainty about how the economy is evolving should be willing to pursue policies that are somewhat more aggressive than might be indicated by simple point estimates of their models. A more aggressive stance against inflation or, for that matter, against deflation guards against the possibility that monetary policy is less effective than the point estimates suggest. It should be emphasized that this conclusion was reached after making many simplifications: the modified Rudebusch-Svensson (1989) model is linear and small, time variation was admitted only for a subset of the parameters, quadratic loss was used, and estimation uncertainty was ignored. An important research question is whether these qualitative conclusions hold up when these simplifications are relaxed.

This paper has focused on the NAIRU and on models involving the unemployment rate. However, if the role of unemployment as an economic indicator is changing, there is a premium on finding other indicators that have more stable links to economic activity. Of the indicators not studied here, some seem likely to be particularly susceptible to measurement problems induced by the shift to knowledge-based production; these include the GDP gap, because of the difficulties in measuring productivity and thus in measuring potential GDP. On the other hand, there are some real quantity indicators, the measurement of which is largely unaffected by the trend towards knowledge-based production. An example of such an indicator is housing starts, which for the U.S. has proven to be a useful demand proxy for forecasting inflation (Stock and Watson (1997b)). One avenue of further research suggested is refining the list of such indicators and assessing the stability of their relation to overall economic activity and to measures of monetary policy.

Table 1

Time-Varying NAIRU Models: United States, 61:1-97:3

dependent variable: change in CPI inflation

Unemployment variable:	total	marr male	male 25-54	male 35-44	dem adj
$\overline{R}^2$	0.391	0.367	0.362	0.424	0.398
$\hat{\beta}(1)$	-0.226	-0.284	-0.196	-0.212	-0.257
(std. error)	(0.080)	(0.098)	(0.068)	(0.070)	(0.079)
QLR statistics testing constancy of:					
intercept	2.41	1.88	3.76	3.27	3.18
intercept and $\beta(1)$	3.52	6.81	6.08	6.33	4.42
Median-unbiased estimate of τ	0.0	0.0	0.021	0.006	0.0
90% confidence interval for τ	(0,0.119)	(0,0.092)	(0,0.181)	(0,0.159)	(0,0.154)

Note: All specifications include four lags each of unemployment and changes of inflation, the contemporaneous value of Gordon's (1982) Nixon wage and price control series, and a single lag of the relative price of food and energy as discussed in the text. The QLR test is significant at the: [+]10%; *5%; **1% level.

Table 2

**Inflation and unemployment in Europe and North America:
the 1990s vs. the 1960s and early 1970s**

Country	Period	Change in inflation	Average unempl.	Avg. unempl. rate, 1960-74
Canada	1993-96	-0.3%	10.2%	5.1%
France	1993-96	-0.1	12.1	2.1
Italy	1993-96	-0.3	11.4	3.3
UK	1992-95	-0.3	9.8	2.9
Germany	1991-93	0.3	4.9	0.7
US	1993-96	0.0	6.0	5.0

Notes: Entries in the column, "change in inflation," are the change
in the annual rate of inflation over the indicated period in the
preceding column, and entries in the "Average Unempl." column are the
average annual rates of unemployment over the same period. The final
column provides the average annual rate of unemployment over the
fifteen year comparison period of 1960-1974.

Table 3

**Correlations Betwen Time-Varying NAIRU (total unemployment)
and Measures of Service Sector Growth U.S.**

| | Income share, | ----- Employment share of: ------ | | |
	services	total serv.	bus. serv	FIRE
Cross-correlations at lag:				
0	-0.12	-0.43	-0.34	0.07
1	-0.17	-0.42	-0.39	0.05
2	-0.13	-0.36	-0.41	0.04
3	-0.18	-0.34	-0.46	0.03
4	-0.13	-0.30	-0.47	0.04
5	-0.15	-0.23	-0.41	0.07
6	-0.10	-0.13	-0.38	0.07
7	-0.09	-0.10	-0.37	0.08
8	-0.05	-0.12	-0.34	0.09
9	-0.06	-0.13	-0.33	0.05
10	-0.13	-0.15	-0.30	0.02
11	-0.08	-0.09	-0.26	0.04
12	-0.05	-0.05	-0.22	0.07
Granger Causality p-value	.078	.456	.031	.986
# observations	141	141	141	129

Notes: All statistics pertain to changes in the TVP-NAIRU estimate (total

unemployment) and changes in the service sector share variable given at the top

of each column. For the Granger-causality regressions, the dependent variable

is the change in the TVP-NAIRU estimate, and four lags of both variables and a

constant were included in the regression. Standard errors for the correlations

are approximately .08.
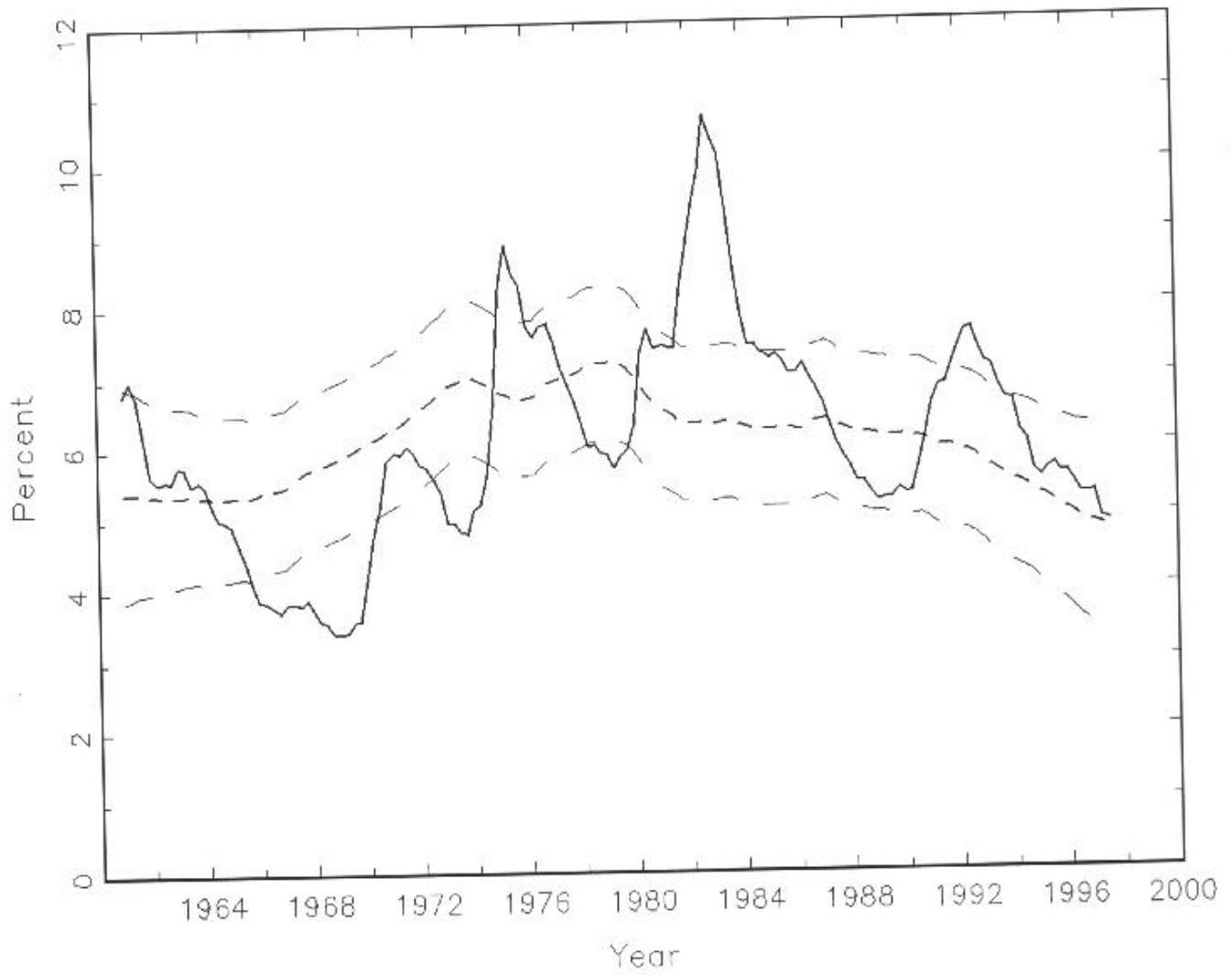
Figure 1

Total unemployment (solid line), time-varying NAIRU (dashed line),
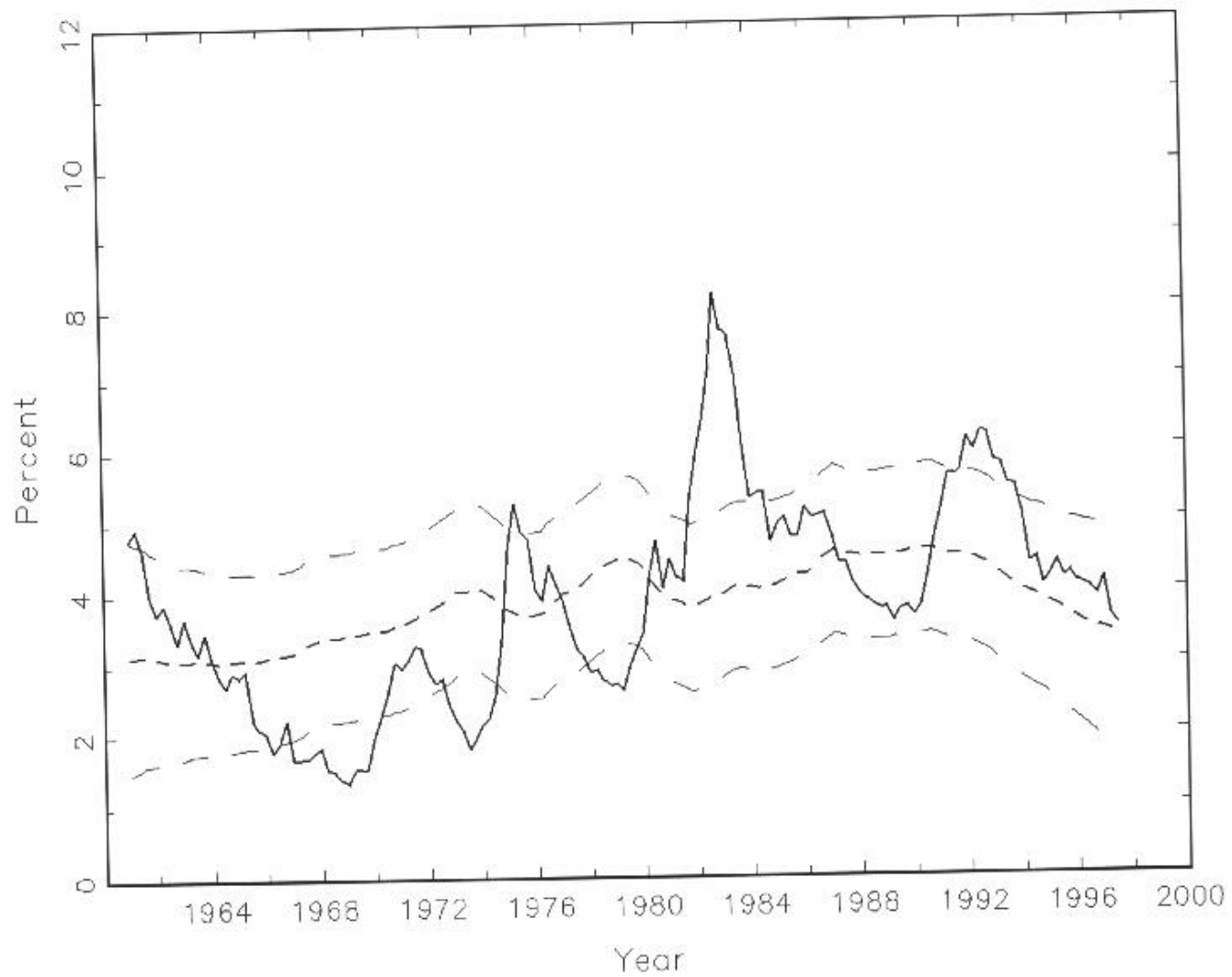and standard deviation bands for the NAIRU, U.S., 1961:1-1997:3

Figure 2

Male unemployment, ages 35-44 (solid line), time-varying NAIRU (dashed line),
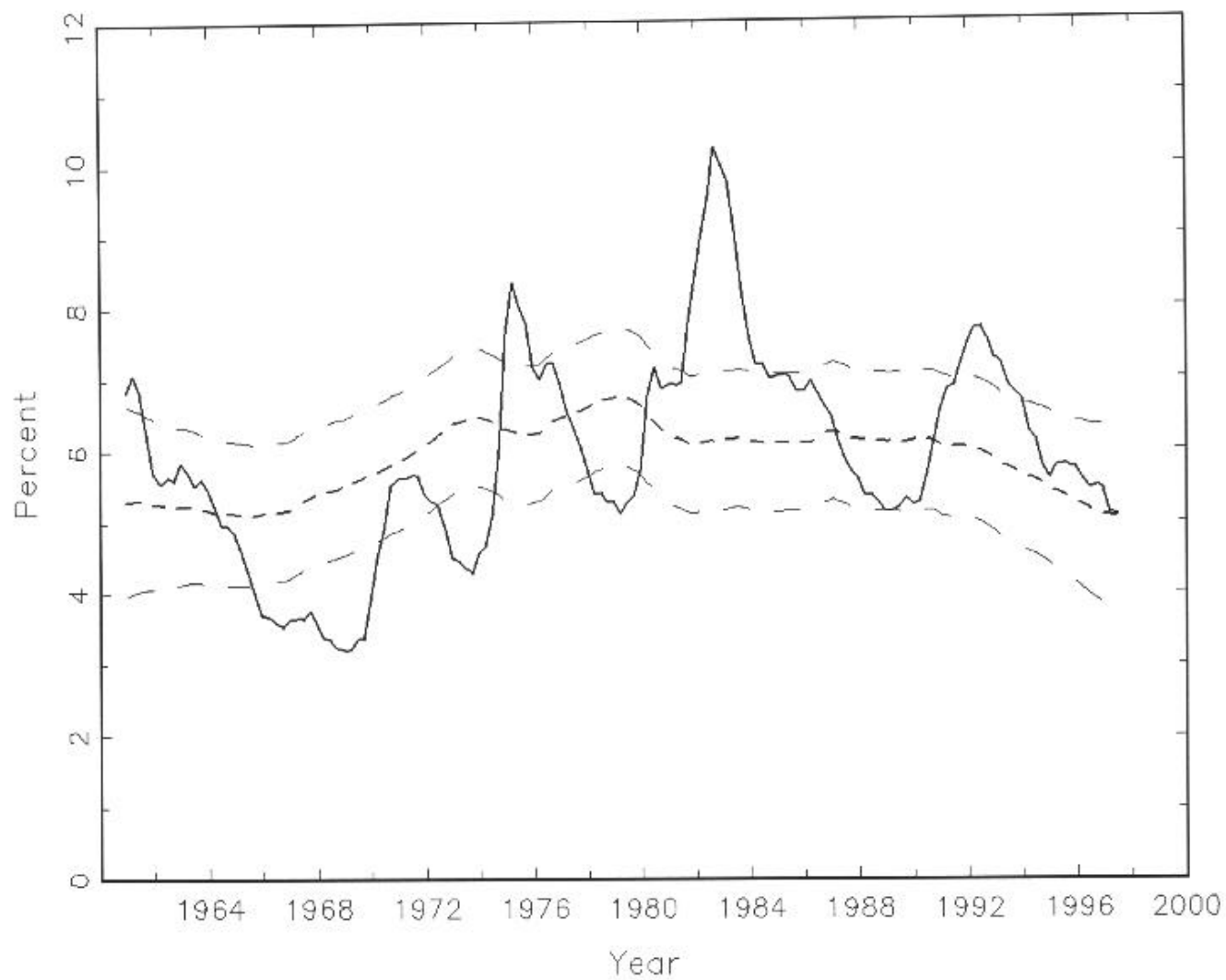and standard deviation bands for the NAIRU, 1961:1-1997:3

Figure 3

Demographically adjusted unemployment (solid line), time-varying NAIRU (dashed line),
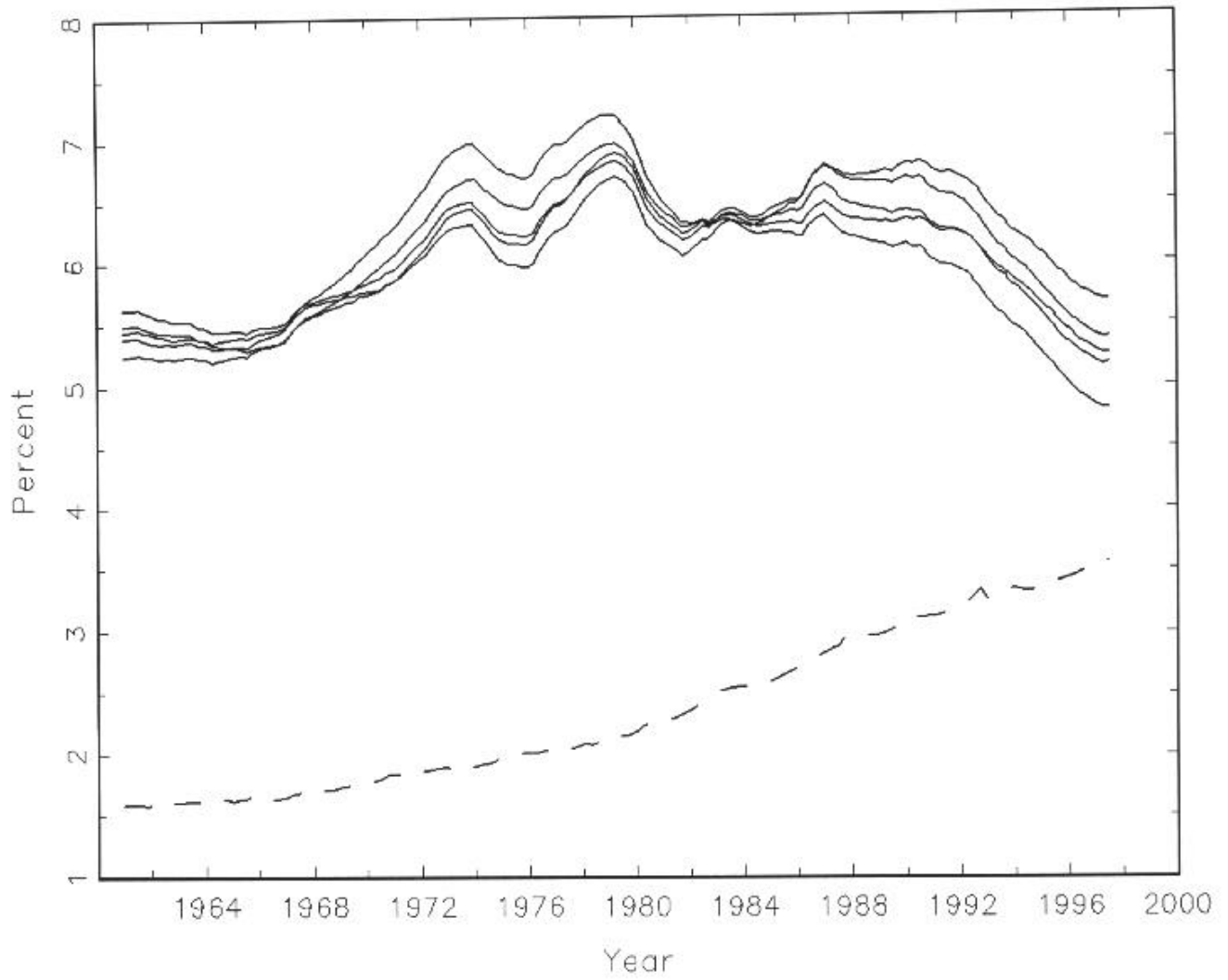and standard deviation bands for the NAIRU, 1961:1-1997:3

Figure 4

Time-varying NAIRUs for the U.S. (solid lines) and

the rescaled income share of all services (dashed line, divided by 10), quarterly
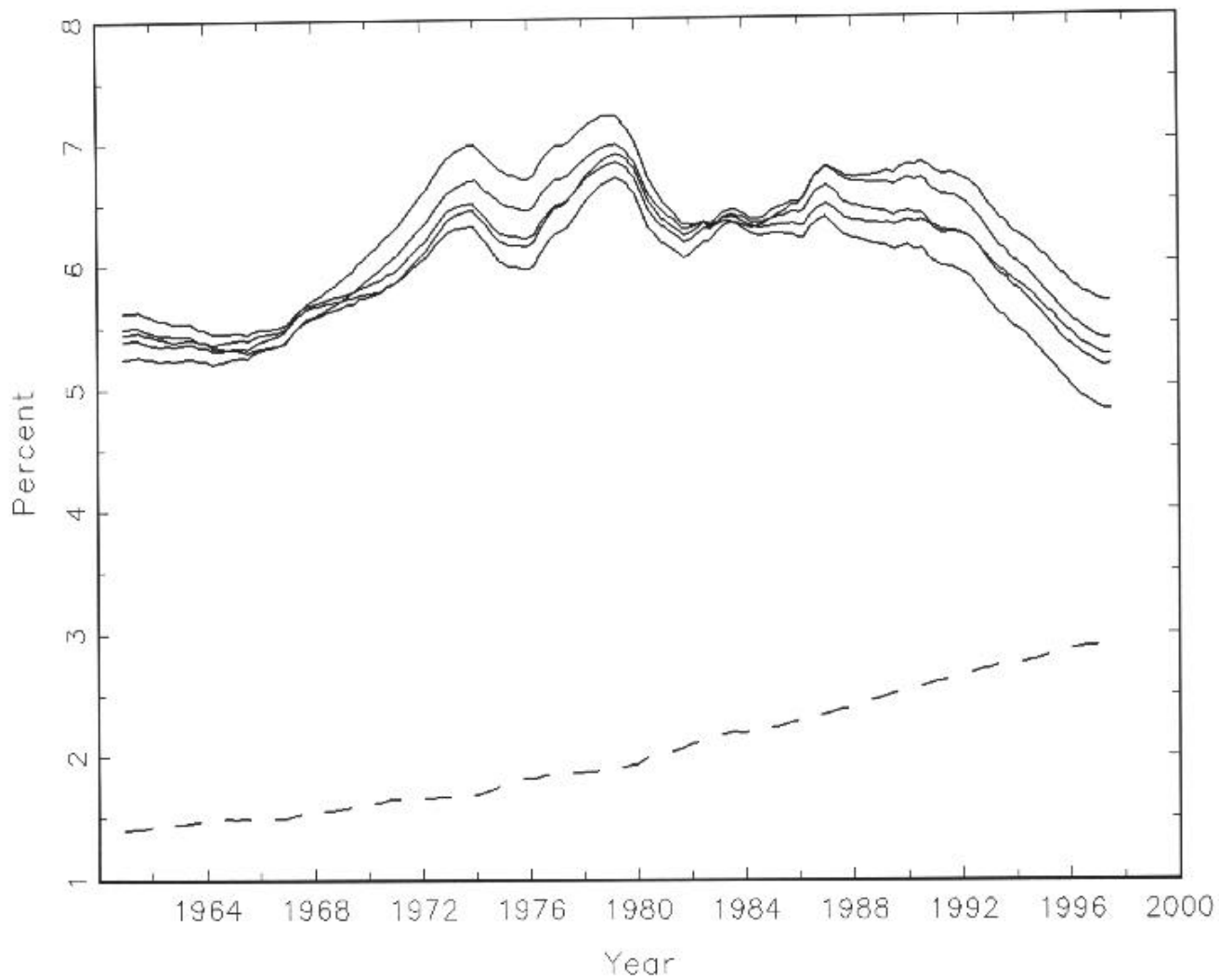
Figure 5

Time-varying NAIRUs for the U.S. (solid lines) and

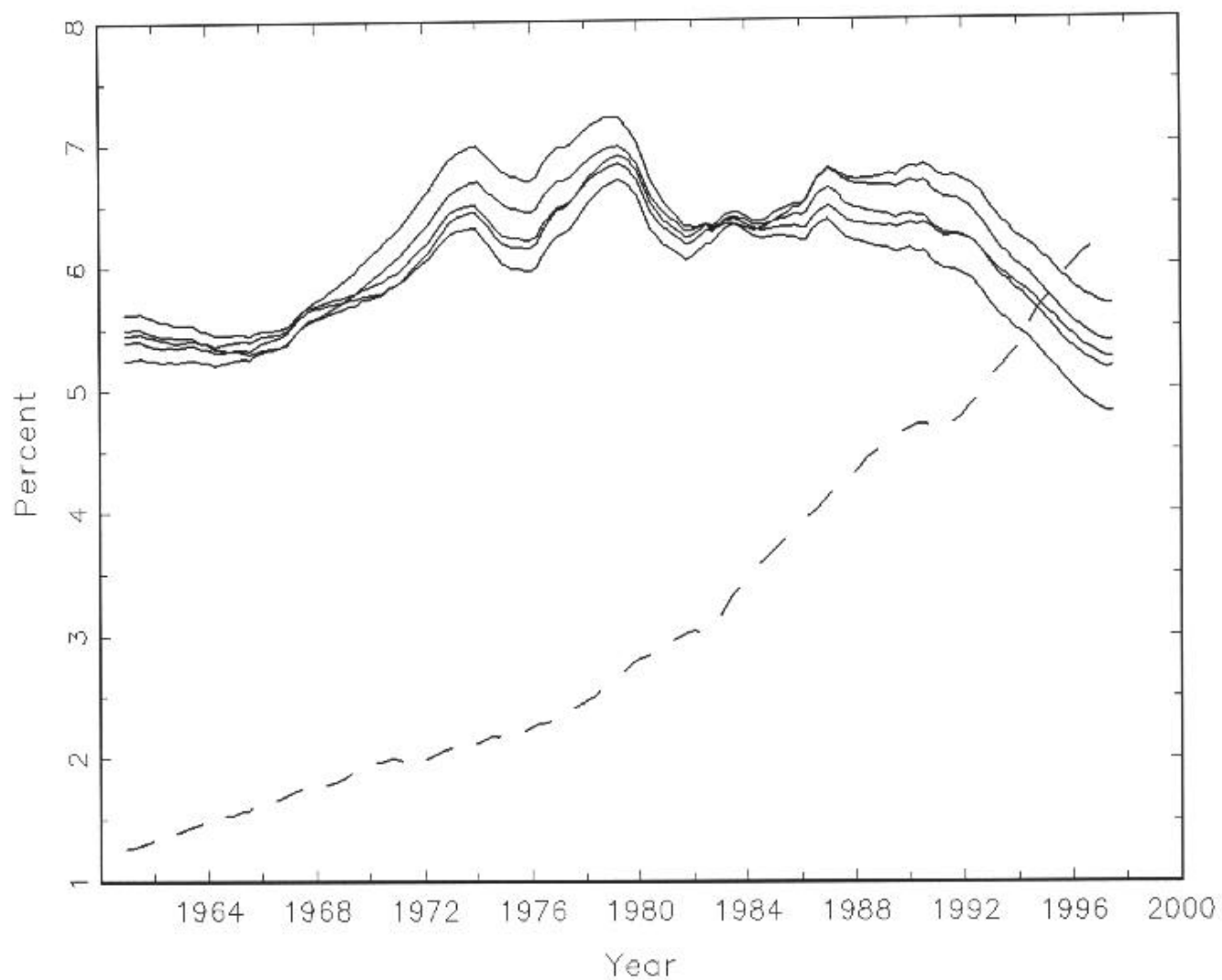the share of employment in all services (dashed line, divided by 10), quarterly

Figure 6
Time-varying NAIRUs for the U.S. (solid lines) and
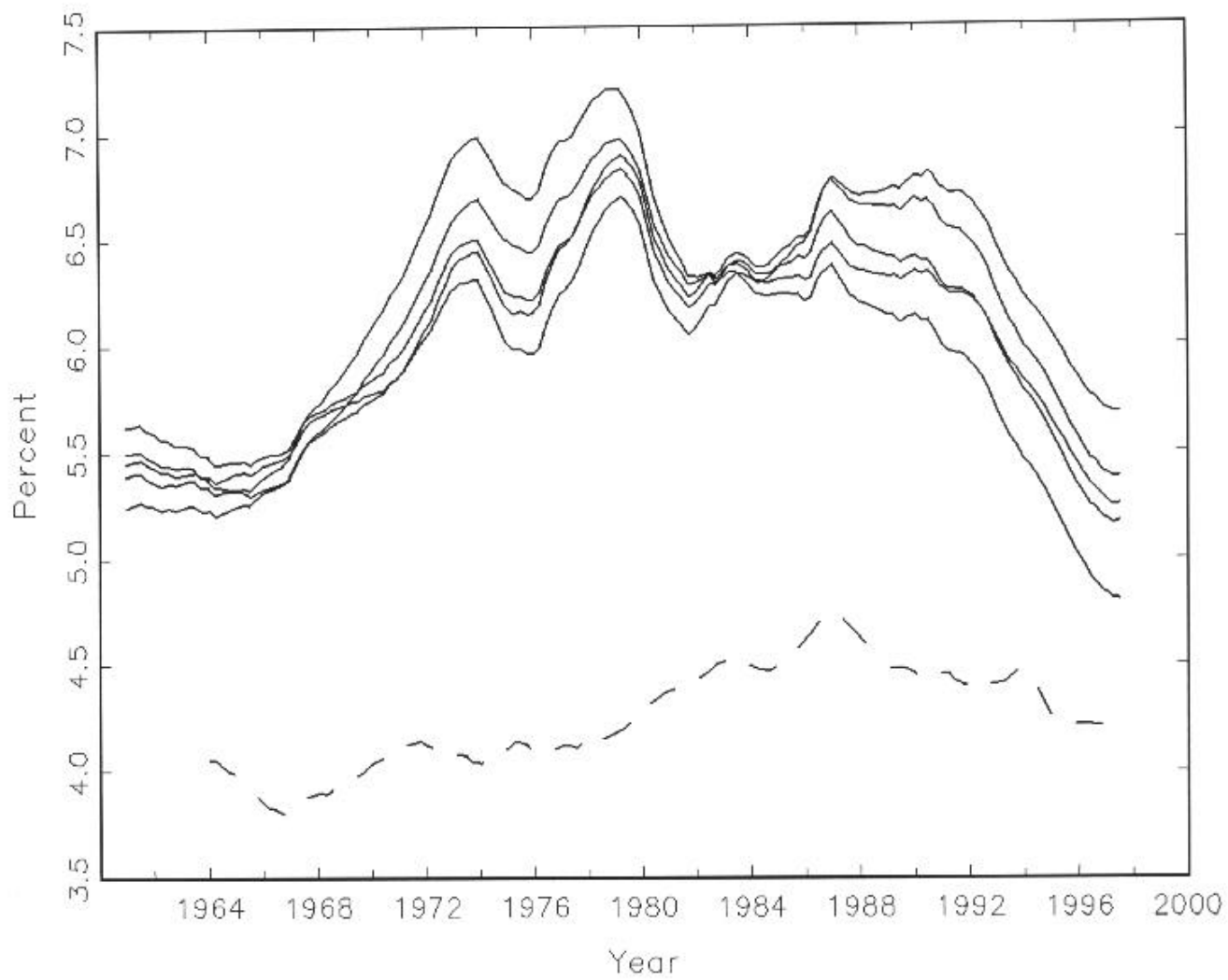the share of employment in business services (dashed line), quarterly

Figure 7

Time-varying NAIRUs for the U.S. (solid lines) and
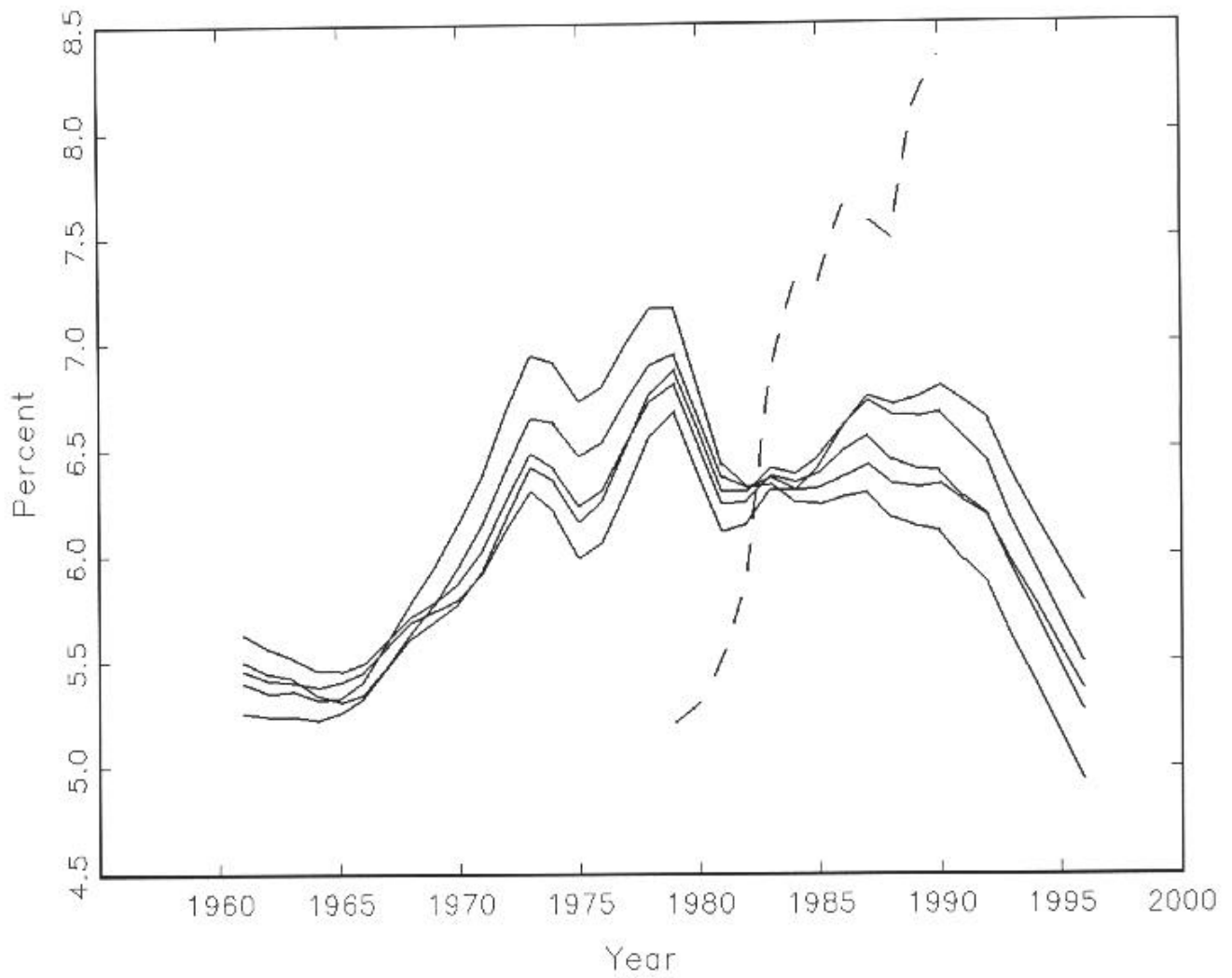the share of employment in finance, insurance and real estate (dashed line), quarterly

Figure 8

Time-varying NAIRUs for the U.S. (solid lines) and
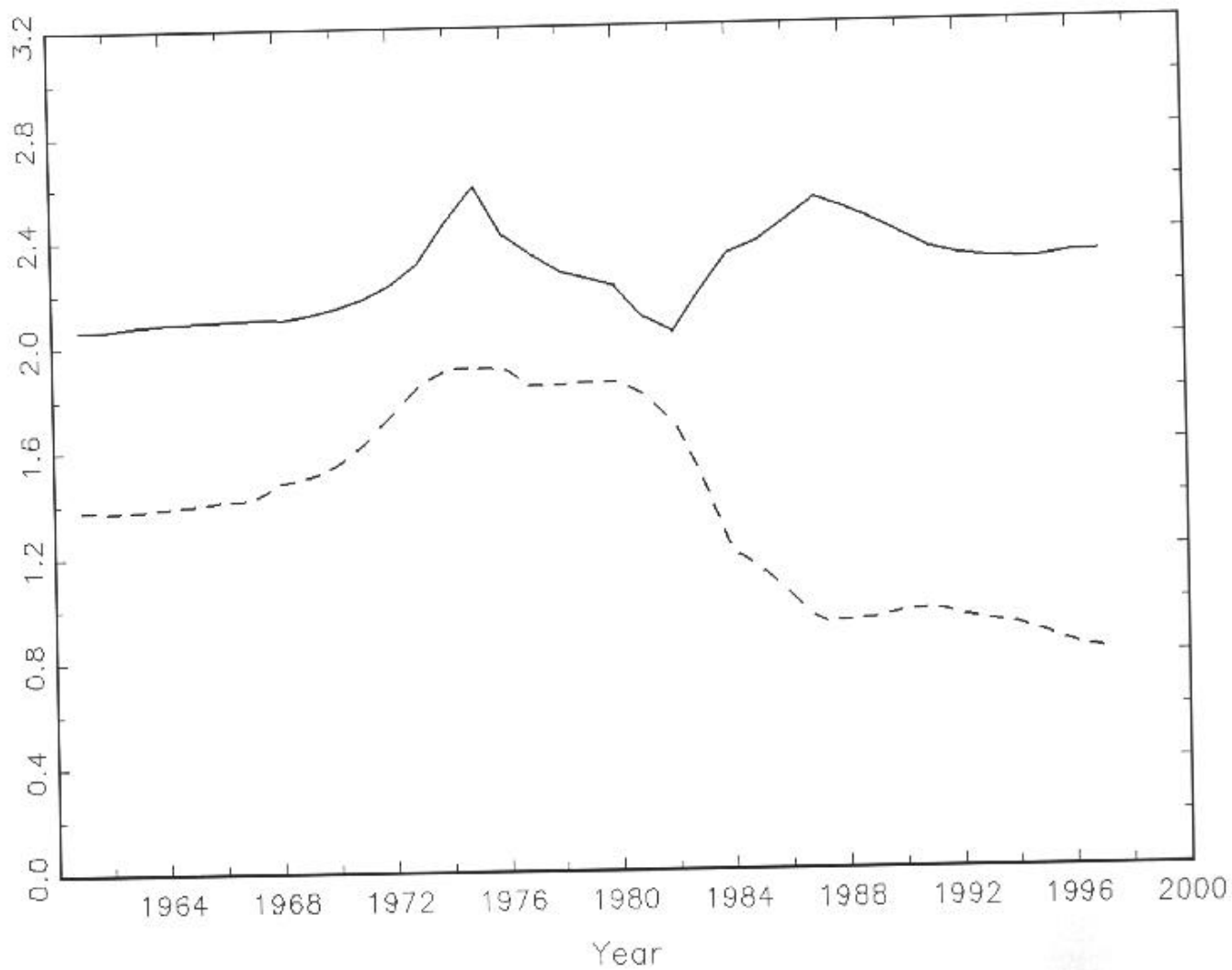the return to an additional year of education (dashed line), annual

Figure 9

Optimized Taylor-type rule parameters, g_π (solid line) and g_u (dashed lines),
for counterfactual, time-varying, historically optimal policies
within modified Rudebusch-Svensson model

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