Is the Taylor Rule Still an Adequate Representation of Monetary Policy in Macroeconomic Models?

James Dean*
North Dakota State University

Scott Schuh†
West Virginia University

December 2022

Abstract

A Taylor Rule remains the consensus specification in macroeconomic models despite new unconventional monetary policies (UMP) and the policy rate near zero in 2009-2015. We find structural breaks at 2007:Q3 in benchmark macro models. Taylor Rule coefficients shift back toward pre-1984 estimates (relative increase in output gap weight). Surprisingly, results are similar for models estimated using the fed funds rate with zero lower bound (ZLB) constraint and using a shadow funds rate to proxy for UMP. Either breaks are not due to UMP or the shadow rate is an ineffective proxy for UMP. However, significant breaks (time variation) in non-policy parameters and model dynamics cloud inference. Explicit specification of UMP structure is likely necessary.

Keywords: Taylor Rule, Structural Break, Macroeconomic Models, Unconventional Monetary Policy

JEL Classifications: E43, E52, E58, E12, E13, E65, E61, C50, C32

*Corresponding Author. *Email*: james.dean.1@ndsu.edu

†*Email*: scott.schuh@mail.wvu.edu

[1]We thank Arabinda Basistha, Peter Ireland, Enrique Martinez-Garcia, and Eric Sims, for helpful comments, as well as participants at West Virginia University's Macro, Money, and Finance Workshop and the 2021 WEAI Annual Meetings. Dean also thanks the Institute for Humane Studies for their support.

1 Introduction

More than a decade after the Global Financial Crisis (GFC) and implementation of unconventional monetary policies (UMP), John Taylor's (1993) interest rate rule remains the consensus specification of monetary policy in macroeconomic models. Prominent examples include the benchmark New Keynesian DSGE model in "Rebuilding Macro Theory" (Vines and Wills 2018); 150 structural models in the Macroeconomic Model Data Base (MMB); textbooks at all levels; and even recent innovations in macro models with monetary policy.[1] The Federal Reserve Board still relies on a prototypical Taylor Rule in its primary macro model, FRB/US:

$$i_t = \rho i_{t-1} + (1-\rho)[r + \pi_t + \phi_\pi(\pi_t - \pi^*) + \phi_x x_t] + \epsilon_t \tag{1}$$

where i_t is the nominal federal funds interest rate, r_t is the "natural" (equilibrium) real rate, π_t is inflation, π^* is target inflation, and x_t is the output gap (Brayton et al., 2014). The Fed's Estimated Dynamic Optimization (EDO) model adds the change in the output gap (Chung et al. 2010). While particular specifications vary, most macro models still include an equation close to this one.

The sufficiency of a single rule like equation (1) based on the federal funds rate as representative of monetary policy is being re-examined. Bernanke (2020) notes that "old methods won't do" when implementing policy, and that "[i]f monetary policy is to remain relevant, policymakers will have to *adopt new tools, tactics, and frameworks*" [emphasis added]. The Fed itself issued a detailed "primer" on the conduct of monetary policy in an "ample-reserves regime" (Ihrig *et al* 2020), and Dudley (2021) argues the fed funds rate target is obsolete so the Fed should use interest on reserves (IOR) instead.[2] Recent research proposes adding a balance sheet rule for Fed bond holdings that emulates the Taylor formula to capture Quan-

[1] A *short* list of innovations includes Gabaix (2020), Barnichon and Mesters (2021), Laurays et al. (2021), and Fuhrer (2017). For details on MMB see https://www.macromodelbase.com/.

[2] See https://www.bloomberg.com/opinion/articles/2021-06-24/the-fed-s-interest-rate-target-is-obsolete

titative Easing (Sims and Wu 2021, Sims *et al* 2021, and Dean 2021). These assessments underscore the likelihood of a structural break in monetary policy after 2007 due to UMP and beg the question: can the Taylor Rule continue to adequately represent the full measure of modern monetary policy in macroeconomic models? On the other hand, Taylor (2021) still advocates the powerful simplicity of his original rule.

We address the paper's title by conducting two econometric tests that provide an initial assessment in what is surely a long-run research program. First, we follow the literature (reviewed in Section 2) and test for structural breaks in 2007:Q3, the boundary between the Great Moderation (1984-2007) and the period between the GFC and COVID-19 pandemic (2008-2019).[3] We use three benchmark macro models that vary in size and degree of structural restrictions for robustness but do *not* include UMP: 1) a VAR with modest restrictions; 2) the three-variable New Keynesian (NK) model of Clarida, Gali, and Gertler (1999, 2000); and 3) the DSGE model of Smets and Wouters (2007). Emergence of UMP should manifest in models without UMP as breaks in either Taylor Rule or non-policy parameters, or both. Rossi (2021) focuses on reduced-form models like our VAR and other creative strategies for identifying monetary shocks. Like Carvahlo et al (2021), we add structural models in search of more detailed identification and understanding, but instead use full-information estimation of the entire macro model.[4] Fernandez-Villaverde and Rubio-Ramirez (2007) advocate a more complex model with "parameter drift" (time-varying parameters). Our simpler discrete approach still qualitatively captures their estimated drift "in an indirect way" (p.87), plus it extends their analysis beyond the early 2000s to the crucial GFC period and beyond.

The second econometric test is a comparison of results using two monetary policy rates: the standard fed funds and a shadow rate that incorporates elements of UMP. Unlike prior research, using the federal funds rate in the Taylor Rule after 2007:Q3 poses two economet-

[3]Although focused on the break in 2007:Q3, the analysis covers 1960-2019 for completeness and comparison with prior studies. The COVID-19 pandemic and recession precipitated additional unconventional policies, such as Fed purchases of commercial bonds and direct loans to small businesses, which are too new to properly evaluate and left for future research.

[4]See Fuhrer, Moore, and Schuh (1995) and West and Wilcox (1996) on the superiority of FIML to GMM and single-equation OLS.

ric challenges. First, the fed funds rate was stuck at the zero lower bound (ZLB) for nearly seven years (2009-2015). This truncation may bias inference for model parameters, so our NK and DSGE models estimated with the fed funds rate include an explicit ZLB constraint.[5] Another challenge is identifying the effects of UMP, as explained in Rossi's (2021) insightful survey. Ultimately, proper identification requires sufficient incorporation of UMP into models' structural equations. Because the literature has not reached a consensus yet on a comprehensive theoretical model, much less an estimated one, we instead use the "shadow" fed funds rate of Wu and Xia (2016) as a proxy for the effects of UMP.[6] The shadow rate indirectly incorporates the effects of Forward Guidance (FG) and Quantitative Easing (QE) on long-term rates via the term structure, which does not appear in the benchmark models, and is not subject to the ZLB constraint. If structural break results with the shadow rate differ significantly from those with the fed funds rate, then the traditional Taylor Rule may no longer be sufficient.

We find statistically and economically significant structural breaks around 2007:Q3 (start of the GFC) in parameters of the Taylor Rule. The breaks are qualitatively and, in most cases, quantitatively consistent across all three models where comparable. The post-GFC Taylor Rules shows the Fed returned to being *less* responsive to changes in *both* inflation and the output gap after 2008, but more so the former. While breaks in Taylor Rule coefficients are larger than the small-sample estimation biases noted in Carvahlo et al (2021), the changes have clear but economically moderate implications for the dynamic responses of the macro models to monetary policy shocks.

Perhaps most surprisingly, results for post-GFC breaks in the Taylor Rule coefficients are essentially the same qualitatively and even quantitatively when the models are estimated with the shadow rate as they are with the fed funds rate and ZLB constraint. The only minor

[5] We use the OccBin method described in Guerrieri and Iacoviello (2015), Cuba-Borda, Guerrieri, Iacoviello, and Zhong (2019), and Giovannini, Pfeiffer, and Ratto (2021). Even prior to the GFC, some papers incorporated the effects of an explicit zero lower bound (ZLB) constraint on the monetary policy rate. For examples, see Fuhrer and Madigan (1997) and McCallum (2000).

[6] See also Krippner (2013) and Bauer and Rudebusch (2014) for alternative shadow rates.

difference is greater persistence in the fed funds rate than the shadow rate, which is logical due to the extended time at the ZLB. This striking result begs two key questions. First, given the large, unconventional nature of known changes in monetary policy, why isn't there clear evidence of a greater effect than the modest changes indicated by the models with the fed funds rate? Second, if the shadow rate is an effective proxy for UMP, why isn't there a much larger difference between the breaks identified by the models with the shadow rate?

One potential explanation that could answer both questions is that the presumption UMP represents a dramatic change in monetary policy is incorrect. If so, one would not expect larger breaks in the Taylor rule post-GFC than the breaks that have been observed in the past, as our estimates suggest. If so, controlling for UMP via the shadow rate would be essentially unnecessary. However, if UMP actually explains most of the observed (modest) break in the Taylor Rule, the answer to the second question could be that the shadow rate is not an effective proxy for UMP.

Unfortunately, this paper cannot definitively discern answers to either question because structural breaks also occurred elsewhere in the models.[7] Indeed, many key aspects of the non-policy structure of the economy changed significantly after 2007:Q3. For examples, agents became more sensitive to changes in the real interest rate and expected inflation; steady state growth and inflation fell; and the Phillips Curve flattened. Some of these breaks (or time variation) may be related to policy changes, as in Lucas (1976). Other coefficient breaks likely are not directly related to monetary policy but could influence the setting of optimal policy. Collectively, individual breaks in the coefficients of the Taylor Rule and non-policy equations manifest as clear but economically modest changes in models' dynamics.

Collectively, the structural breaks in model coefficients manifest themselves in economically significant changes in three key dynamic characteristics of the estimated models. Structural shocks estimated over subsamples exhibit change in their relative volatility and autoregressive properties, which influences estimation of the Taylor Rule (Carvahlo et al., 2021).

[7] This finding is consistent with continuous time variation in coefficient point estimates and variances identified by Fernandez-Villaverde and Rubio-Ramirez (2007, 2010).

After 2007:Q3, the variance and persistence of DSGE monetary shocks increased, and properties of other shocks changed as well.[8] The models' dynamic properties (impulse responses) also vary across subsamples. Dynamic differences are less evident when all parameters are allowed to change, but counterfactual exercises holding either Taylor Rule or non-policy coefficients fixed at full-sample estimates show considerably larger differences across subsamples. After 2007:Q3, the DSGE output and inflation responses to monetary policy shocks reverted back their magnitudes before the Great Moderation, which now looks more like an outlier period. Finally, subsample breaks in DSGE coefficients significantly affect estimates of the model-consistent output gap. The full-sample output gap deviates significantly from the Congressional Budget Office (CBO) output gap used by the VAR and NK models. The break-adjusted DSGE output gap much more closely resembles the CBO gap.

The magnitudes and prevalence of breaks in non-policy structural parameters suggests that time-variation in aspects of the macro models is an important but missing feature of the benchmark macro models. Thus, it is difficult to tell from the estimated benchmark models—with or without a shadow rate—whether the observed breaks reflect time-variation unrelated to UMP rather or are the effects of UMP. Perhaps the most likely time variation occurred in steady state output growth and the natural real rate of interest. Controlling for time-variation in these and other variables and equations is an important extension of the benchmark models necessary for more conclusive break tests in future research.

Ultimately, it is likely necessary to include explicit, comprehensive structure that fully incorporates UMP. In the benchmark models, this limitation may be leading to an omitted variables (and equations) problem that appears as structural breaks in the estimated parameters. The natural remedy is include explicit, comprehensive specifications of UMP in the macro models. Efforts to do so are emerging but still limited thus far. Introduction of FG after 2007:Q3 mainly has been modeled and estimated (or calibrated) as the addition

[8]This finding follows the result in Fernández-Villaverde and Rubio-Ramírez (2010) that time series often exhibit changes in volatility over time, and that must be modeled to adequately take account of the data.

of policy announcement shocks to the Taylor Rule.[9] Modeling QE has occurred mainly in theoretical models that introduce banks and their balance sheets to capture bond holdings and bank reserve management.[10] One promising paper that combines these two strands is Wu and Zhang (2019), which microfounds a central bank's bond holdings in an effort to map unconventional policies into a single "shadow" fed funds rate to be used in a standard Taylor Rule. Estimated macro models with explicit UMP specifications would be better-suited to identify the effects of recent policy changes.

2 Previous Literature

Table 1 lists the main papers reporting evidence on structural breaks in the Taylor Rule. The structure of the Rule has stayed largely the same as the original specification except for the addition of persistence (i_{t-1}), allowance for output dynamics (growth rate or gap change), and variation in lags or other practical features, as shown in Coibion and Gorodnichenko (2012).[11] The literature contains a variety of different modeling and econometric methods used to estimate breaks in the Taylor Rule coefficients. However, the results tend to be broadly consistent across papers.

Regime-switching models and break point tests, like those in Estrella and Fuhrer (2003) and Duffy and Engle-Warnick (2004) consistently show a regime change somewhere in the late 1970s or early 1980s followed by another in the mid 1980s. This result follows closely with the traditional narrative that the Federal Reserve undertook a "Monetarist experiment" during this period, wherein the Fed targeted the growth of a monetary aggregate rather than an interest rate. Using a single-equation model, Bunzel and Enders (2010) find these regimes appear in the Taylor Rule as a regime characterized by strong output gap and inflation responses (1970s) followed by a regime characterized by gradual adjustment of the federal

[9] For more on forward guidance, see Del Negro, et. al (2012), Bundick and Smith (2016), Campbell et. al (2017) and McKay et. al (2016).

[10] For examples on modeling QE, see the Gerler and Karadi (2011, 2013) and Joyce et. al (2012).

[11] For examples, see the monetary policy rules in Macro Modelbase: `https://www.macromodelbase.com/files/documentation_source/mmb-mprule-description.pdf?40780101f6`.

funds rate (post 1980s). However, Estrella and Fuhrer (2003) note that these regime changes could be caused by changes elsewhere in the economy that smaller, single-equation models cannot estimate. Further, as Carvalho et al. (2021) show, the estimation methodology is important to any examination of Taylor Rule coefficients. Any estimation of monetary policy is subject to an endogeneity issue, as the central bank influences and responds to changes in inflation and output. Nevertheless, Carvalho et al. (2021) find that simple OLS estimates of the Taylor Rule still outperform IV estimates while still producing largely consistent model dynamics.

Researchers also have attempted to find structural breaks in VAR models. Using a factor-augmented VAR, Bernanke and Mihov (1998) find that no simple policy variable fully captures monetary policy from 1965-1996. Instead, they find regime switches in the Fed's operating procedure in roughly 1979 and 1982, similar to the single-equation break-point models. Using structural VARs, Primiceri (2005) and Sims and Zha (2006) find similar timing of the regime changes but emphasize they are characterised by changes in the *variance* of Taylor Rule coefficients, as well as changes in the coefficient point estimates. In essence, the structural VARs suggest that monetary policy after the mid-1980s is characterized best by more consistent responses to output and inflation.

Other researchers estimated changes in the Taylor Rule using full structural models. Using an RBC model with money for 1966-1982 and 1990-2006 subsamples, Castelnuovo (2012) finds the Taylor Rule parameters are largely unchanged across subsamples, but the fed funds rate is less responsive to money growth in the second sample. Coibion and Gorodnichenko (2011) find that, while the Fed satisfied the Taylor principle in the 1970's, changes in the Taylor Rule induced determinacy during the Volcker disinflation, helping stabilize inflation. Using the same NK model and Bayesian methods as this paper (Clarida, Gali, Gertler 1999), Canova (2009) finds the Fed responds more strongly to inflation after 1982, likely contributing to the Great Moderation (Stock and Watson 2002). Using the Smets and Wouters' (2007) model for 1966-1979 and 1983-2005 subsamples, Ilbas (2012) similarly finds the Fed is more responsive to inflation after 1983 as well as greater interest-rate smoothing and a lower inflation target during the Great Moderation era. Fernández-Villaverde and Rubio-Ramírez (2007) add to this body of literature by examining parameter drift, rather than clean structural breaks. They find that these deeper "structural" parameters tend to exhibit a drift over time, and parameters are likely to have substantial variation in larger samples.

3 Models

We use three benchmark macro models to estimate the Taylor Rule and test for structural breaks. For robustness, the models vary in size (small- to medium-scale) and degree of structure (few to many cross-equation restrictions).

3.1 Taylor Rules

The models contain two slightly different variants of the Taylor Rule. The VAR and NK models include a simplified version of the FRB/US Taylor Rule (equation 1),

$$i_t = \rho i_{t-1} + (1-\rho)[\phi_\pi(\pi_t - \pi^*) + \phi_x x_t)] + \epsilon_t \ , \tag{2}$$

which assumes a (suppressed) constant equilibrium nominal rate ($r + \pi^*$). The output gap, $x_t = (y_t - y^{POT})$, uses potential output (POT) from the Congressional Budget Office.[12] The DSGE model adds short-run feedback from the change in the output gap as Smets and Wouters (2007):

$$r_t^f = \rho r_{t-1}^f + (1-\rho)[\phi_\pi \pi_t + \phi_y(y_t - y_t^p)] + \phi_{\Delta y}[(y_t - y_t^p) - (y_{t-1} - y_{t-1}^p)] + \epsilon_t \ , \tag{3}$$

[12]See https://www.cbo.gov/data/budget-economic-data.

where $r_t^f = i_t$ to momentarily sidestep notation conflict (SW use i for investment and r for the nominal rate); henceforth, i_t is the nominal rate unless noted otherwise. Equation (3) uses the DSGE concept of potential output, y^p, which denotes the level that would prevail if prices were flexible and there were no markups. Estimates of ρ and the ϕ parameters provide evidence on stability of the Taylor Rule across subsamples. In contrast, Carvahlo et al. (2021) estimate their models with a Taylor Rule in which the Fed only targets inflation, rather than inflation and the output gap.

Neither the Taylor Rules nor the macro models incorporate UMP. However, some papers have incorporated Forward Guidance (FG) into the Taylor Rule using the effective fed funds rate and FG shocks to the future policy rate as follows:

$$i_t = \rho i_{t-1} + (1-\rho)[\phi_\pi(\pi_t - \pi^*) + \phi_x x_t)] + \epsilon_t^{MP} + \sum_{l=1}^{L} \epsilon_{l,t-l}^{R} \tag{4}$$

where $\sum_{l=1}^{L} \epsilon_{l,t-l}^{R}$ are FG shocks to the interest rate at time l, but realized at $t-l$ and ϵ_t^{MP} are the standard monetary shocks.[13] A FG shock is the difference between actual i_t and the expected rate announced by the central bank at time $t-l$. Thus, FG on future policy rates essentially extends the duration of the short-term rate at the ZLB.[14]

Although the FG-augmented Taylor Rule does not account explicitly for the quantitative easing (QE) portion of UMP, it is mathematically similar to the FG shock in the literature on QE and shadow federal funds rates. As noted by scholars from Black (1995) to Rossi (2021), the shadow rate is an option, i.e., the short-term interest rate implied by a model of the yield curve. Wu and Zhang (2019) provide a mapping of QE into a standard NK model through the shadow rate. To do this, they assume the shadow rate, s_t, follows the Central

[13]See Del Negro et al. (2012), Campbell et al. (2012), and Cole (2021). This specification also is called "forecast targeting" by Svensson (2017). Reserch with such models find a "Forward Guidance puzzle" of excessively large responses to FG news. The shadow fed funds rate controls for the effects of FG.

[14]See Section 7 for more discussion of the relationship between FG and UMP.

Bank (CB) balance sheet according to:

$$s_t = -\zeta(b_t^{CB} - b^{CB}) + \epsilon_t^{FG} + \epsilon_t^{MP} \tag{5}$$

where ζ maps the shadow rate to the difference between bond holdings, b_t^{CB}, and their steady state level and ϵ_t^{FG} is forward guidance, and ϵ_t^{MP} is the difference between the actual and predicted shadow rates.

Figure 1 shows the shadow rate closely tracks Fed bond holdings with only three key deviations, which Wu and Zhang (2019) note coincide with the Fed's changes in FG. The early 2010 deviation coincides with the Fed signaling it would unwind its lending facilities. The 2014 decline coincides with the Fed extending its forecasted duration of the ZLB. And the early 2013 spike coincides with the so-called Taper Tantrum and is presented as a traditional monetary shock. In other words, deviations of the shadow rate from the Fed's balance sheet present themselves similarly to the FG shock.

In short, by using the shadow rate we avoid the need to include the forward guidance augmented Taylor Rule in our estimation because s_t incorporates forward guidance. Moreover, s_t also includes the effect of quantitative easing, allowing us to incorporate both aspects of unconventional monetary policy. Henceforth, we refer to the interest rate as $\hat{i}_t$ where:

$$\widehat{i}_t = \min(i_t, s_t) \tag{6}$$

to economize on notation later. The advantage of using the shadow rate is it allows for uniform comparison of the stance of monetary policy across conventional and unconventional policy periods. However, as Krippner (2019) notes, shadow rates are sensitive to their assumption of the lower bound. For robustness, we also estimate our models with the actual fed funds rate and use the zero lower-bound specific estimation strategy discussed in Section 4.

3.2 VAR Model

The VAR model is based on the three-variable vector, $Z_t = [x_t, \pi_t, \widehat{i}_t]'$ that includes the output gap, inflation (π_t) and sample-specific policy rate. Abstracting from constant terms, the structural form is

$$B_0 Z_t = \sum_{i=1}^{k} B_i Z_{t-1} + u_t \ , \tag{7}$$

where the 3x1 vector of structural shocks, u_t, is identified from the Cholesky decomposition

$$B_0 = \begin{bmatrix} 1 & 0 & 0 \\ \kappa & 1 & 0 \\ (1-\rho)\phi_x & (1-\rho)\phi_\pi & 1 \end{bmatrix} \tag{8}$$

with usual diagonal covariance matrix, $\Sigma = u_t u_t'$: The ordering restrictions allow the output gap to respond only to its own innovations and hence move the slowest. Inflation responds contemporaneously to the output gap and its own innovations, while the Fed's policy rate responds to shocks in both the output gap and inflation as in the standard Taylor Rule.

This ordering identification originated with Sims (1980) but still is central to Rossi's (2021) contemporary analysis. Our modest structural extension imposes interest-rate smoothing by restricting $\rho = \Gamma_{3,1}$, which is the (3,1) element of the first lag ($k = 1$) of the reduced-form coefficient matrix, $\Gamma_1 = B_0^{-1} B_1$.

3.3 New Keynesian (NK) Model

The three-equation NK model is from Clarida, Gali, and Gertler (1999, 2000) and uses the same variables as the VAR. In addition to the Taylor Rule in equation (2), the NK model imposes structural restrictions in the form of the IS equation and forward-looking Phillips Curve:

$$x_t = \psi[\widehat{i}_t - E_t \pi_{t+1}] + E_t x_{t+1} + \epsilon_{x,t} \tag{9}$$

$$\pi_t = \kappa x_t + \beta E_t \pi_{t+1} + \epsilon_{\pi,t} \tag{10}$$

where β is the discount factor, ψ is the coefficient of relative risk aversion, and κ is the slope of the Phillips Curve. Structural shocks $\epsilon_{x,t}$, $\epsilon_{\pi,t}$, and $\epsilon_{i,t}$ follow an AR(1) process:

$$\epsilon_{j,t} = \rho_j \epsilon_{j,t-1} + \eta_{j,t} \tag{11}$$

where $j = \{x, \pi, i\}$ with $0 < \rho_{j,t} < 1$ capturingthe persistence of shocks and $\eta_{j,t}$ is i.i.d. with zero mean and variances σ_j^2. The model has nine parameters: six structural parameters (β, ψ, κ, ρ, ϕ_π, ϕ_y) and three auxiliary parameters (ρ_x, ρ_π, ρ_i).

3.4 DSGE Model

The medium-scale DSGE model is from Smets and Wouters (2007), which contains the full linearized version. In addition to the Taylor Rule in equation (3), the portion of the DSGE model that most closely matches the NK model are the consumption Euler equation and expectations-augmented NK Phillips Curve:

$$c_t = c_1 c_{t-1} + (1 - c_1) E_t c_{t+1} + c_2 (l_t - E_t l_{t+1}) - c_3 (i_t - E_t \pi_{t+1} + \varepsilon_t^b) \tag{12}$$

$$\pi_t = \pi_1 \pi_{t-1} + \pi_2 E_t \pi_{t+1} - \pi_3 \mu_t^p + \varepsilon_t^p \tag{13}$$

where c_t is real consumption, l_t is hours worked, μ_t^p is the price markup, and ϵ_t^b, ϵ_t^p are structural shocks. The c_i and π_i are parameters to be estimated.[15]

The DSGE model is more comprehensive and imposes stronger cross-equation restrictions than the NK model. For example, the NK IS Curve (9) is obtained from the simplifying assumption that $y_t = c_t$ in the forward-looking consumption Euler equation. The DSGE model does not impose this assumption but explicitly models the entire aggregate resource constraint. Similarly, the NK Phillips Curve (10) is the linearized form of the firm's simplified

[15] For a more comprehensive summary of the SW DSGE model, see Chung, Herbst, and Kiley (2015).

exogenous pricing decision. The DSGE model adds backward- looking elements into the consumption Euler equation and Phillips Curve plus a price mark-up in addition to sticky price adjustment.

The DSGE model has other advantages. It is consistent with a steady-state growth path, incorporating investment decisions and the pricing and accumulation of capital into its optimization problems. The DSGE model also has a more complex stochastic environment with seven structural shocks (productivity, technology, risk premium, spending, monetary, price-markup, and wage-markup) compared with three (demand, cost-push, and monetary), allowing richer and more flexible estimation of the effects of monetary policy.

4 Econometric Specifications

Most data used in this paper come from the FRED database created by the Federal Reserve Bank of St. Louis. The VAR and NK models use: 1) the output gap constructed with the CBO's real potential GDP; 2) core PCE inflation; and 3) the short-term policy rate, $\widehat{i}_t$. The DSGE model uses the same data as Smets and Wouters (2007) but is updated and extended through 2019 and also uses $\widehat{i}_t$. The shadow federal funds rate comes from Wu and Xia (2016) .[16]

4.1 Selection of Samples

The full data sample runs from 1960:Q1 to 2019:Q4. The starting period is consistent with the literature and constrained by availability of the PCE price index data. We truncate the sample in 2019 to exclude the new UMP that emerged during the COVID-19 pandemic and recession. The period during which the Fed targeted non-borrowed reserves (1979:Q4 to 1982:Q4) is included in the full sample rather than using arbitrary estimation methods

[16] See https://sites.google.com/view/jingcynthiawu/shadow-rates?authuser=0

to address missing observations.[17]

Based on the literature and conventional wisdom about known breaks in monetary policy, the subsamples are: I) 1960:Q1 to 1978:Q4; II) 1984:Q1 to 2007:Q2 (Great Moderation); and III) 2007:Q3 to 2019:Q4 (Global Financial Crisis, or GFC). The entire period 1979:Q1 to 1983:Q4 is omitted from subsamples I and II to avoid complications associated with policy changes to and from targeting of non-borrowed reserves, and because the exact dates of the estimated break points in the literature are heterogeneous (Table 1). Differences between econometric estimates from periods I and II are clearer this way, but the results are qualitatively similar (robust) to results when the non-borrowed reserve period is included in either period I or II (or in between). The beginning of sample III (2007:Q3) corresponds to the Fed's initial rate cuts and early events of the financial crisis, such as American Home Mortgage's bankruptcy, BNP Parabas noting a decline in liquidity, the Dow Jones Industrial Average's peak.

For robustness, we provide some formal evidence on the selected break points by estimating a split-sample Chow test for the VAR and testing for structural breaks (Lutkepohl, 2013). Figure 2 shows the p-value from the rolling window estimation; the horizontal dashed line indicates the 5 percent confidence level. The Chow test largely confirms our *a priori* reasoning on the subsample selection: structural breaks corresponding to the Fed's changes in operating procedure in 1979Q3 and 1983Q1, as well as one near the start of the financial crisis in 2007Q3 (both indicated by the vertical dashed lines). For this reason, we continue the tradition in the literature of setting the break periods exogenously rather than using more complicated endogenous break-point methods. Additional potential breaks during the first subsample (I) are assumed not to be associated with monetary policy.

[17] Although the period of monetary targeting is volatile and influential in estimation, it is less so in the full sample than in the shorter subsamples.

4.2 Estimation

The VAR is estimated using OLS so these Taylor Rule estimates are consistent with the recommendation of Carvahlo et al. (2021). The model has $k = 1$ lag for each sample for consistency and to conserve on degrees of freedom. The structural parameters are derived from B_0 and the first own-lagged coefficient in the $\widehat{i}_t$ equation. Standard errors are obtained from the "delta" method (Oehlert, 1992).

The NK and DSGE models are estimated with standard Bayesian methods. Selection of priors has a significant bearing on the estimated parameters, so changing priors between subsamples can potentially bias results toward a structural break when one does not truly exist. To mitigate this bias, and for consistency with earlier research, we use the same prior distribution, mean, and standard deviation in the full sample and all subsamples: Canova's (2009) for the NK model and Smets and Wouters' (2007) for the DSGE model.[18] The likelihood function is calculated using the Kalman filter. The posterior density distribution is obtained from the calculated likelihood function and prior distributions, continuing until convergence is achieved. Then the Metropolis-Hastings algorithm is used to create 2,000 draws of the posterior distribution and approximate moments of the distribution.[19] The ZLB estimation follows the method described in Cuba-Borda et al. (2019) and Giovannini, Pfeiffer, and Ratto (2021) which "turns off" the monetary shock while interest rates are at the lower bound so as to avoid over-interpreting small movements in the interest rate, leading to biased results.

Following Smets and Wouters (2007), the DSGE output gap is generated from the model as the deviation from the level of output that would prevail with flexible wages and prices, y_t^p. This model-generated output gap differs from the output gap used in the VAR and NK models in two ways. First, the latter uses CBO's estimate of potential output derived from

[18] See Appendix A for a list of parameters, their roles in the model, and their priors.

[19] Estimation is performed using a modified version of Johannes Pfeifer's dynare code for Smets and Wouter's model. Pfeifer's code can be found at `https://github.com/JohannesPfeifer/DSGE_mod/tree/master/Smets_Wouters_2007`, and Dynare can be downloaded at `https://dynare.org`.

an independent growth-accounting framework.[20] Second, because CBO estimates potential output for the *full sample* it does not change across subsamples; in contrast, the DSGE output gap is estimated separately for each subsample and thus is subject to breaks in the models' structural parameters.

5 Estimation Results

Tables 2 and 3 report coefficient estimates and evidence of structural breaks in model parameters for the Taylor Rule and other non-policy coefficient estimates, respectively, in the full sample (Full) and each subsample (I-III). There are two subsample III periods depending on which funds rate is used: III$\hat{i}$ (shadow funds rate) and IIIi (fed funds rate). The tables also include coefficient changes between subsamples and, for the VAR model, significance of the t-tests for differences. As noted in Section 2, the break-test results for subsamples I and II are generally consistent with the prior literature, so this section focuses on comparing subsamples II and III. Coefficient magnitudes may vary across models due to differences in model variables and structure, and thus should be compared mainly across subsamples within models.

5.1 Taylor Rule Parameters

During the Great Moderation, the estimated coefficients (Table 2, column II) are broadly consistent with the prior literature.[21]The Fed responds more to the inflation gap than output gap when setting interest rates i.e., $\phi_\pi >> \phi_y$.[22] The difference between these coefficients is largest in the DSGE model (1.97 versus .09). Interest rate persistence is similar across models but a bit lower in the NK model (approximately .6 versus .8). The DSGE's response

[20]See Shackleton (2018), `https://www.cbo.gov/system/files/115th-congress-2017-2018/workingpaper/53558-cbosforecastinggrowthmodel-workingpaper.pdf`.

[21]Specifically, the Great Moderation point estimates for ϕ_π are consistent with those estimated in Carvalho et al. (2021) via both OLS (2.75) and IV (2.63). While the subsample I estimates differ, their estimates have high standard errors.

[22]Similarly, (ϕ_π/ϕ_y) is larger in subsample II than I

to output growth ($\phi_{\Delta y}$) is significant. Estimates of ϕ_π, ϕ_y, ρ in Periods I and II (1.48-1.97; .09-.15; .80-.84) are similar to the analogous full-sample (1962-2008) estimates from **Carlstrom et al 2017** (1.42; .49; .77) with a long-rate target policy rule and term premium in the Taylor Rule.

After the GFC, the estimated coefficients (column III$\widehat{i}$) generally remained statistically significant but tended to revert back toward their period-I values (column I). In all three models, the Fed became less responsive to inflation as ϕ_π declined by economically large and statistically significant amounts, although the VAR estimate (-1.61) is the wrong sign and not significantly different from zero. Changes in other coefficients generally were smaller in absolute value and less systematic and significant. The response to output (ϕ_y) increased (.12) significantly in the DSGE model but declined significantly in the VAR (-1.02) and insignificantly in the NK model ($-.05$). Persistence (ρ) increased significantly (.16) in the NK model but decreased significantly ($-.09$) in the DSGE model and was essentially unchanged in the VAR. The Fed's response to output *growth* ($\phi_{\Delta y}$) was essentially unchanged.

Perhaps surprisingly, coefficient estimates with the actual fed funds rate (IIIi) are quite similar to those using the shadow rate (III$\widehat{i}$), as shown in Table 2. In fact, the coefficient magnitudes are essentially the same statistically with only a few key exceptions. In the VAR model, ϕ_π is positive and much larger but still not significantly different from zero. In the NK model, ϕ_y is larger in the ZLB estimation (.87 versus .64). And in the DSGE model, the interest rate is economically more persistent (ρ=.83 versus .75), presumably because the funds rate was constrained by the ZLB from 2009-2015. The striking similarity between columns III$\widehat{i}$ and IIIi raises questions about the extent to which the shadow funds rate proxies for UMP.

Changes in estimated Taylor Rules during period III show a decline in ϕ_π relative to ϕ_y for both the shadow and fed funds rates. This result could reflect changes in the preferences of monetary policy makers, as was suggested for previous breaks in Taylor Rule coefficients.[23]

[23] Breaks during the Great Moderation (period II) were described as a shift in the preferences of FOMC members toward favoring inflation stability by Canova (2009), Castelnuovo (2012), Ilbas (2012), and Lak-

Bordo and Istrefi (2018) find the FOMC shifted toward being dominated by Doves (higher weight on the output gap) after the GFC (period III). Kocherlakota (2018) goes further, arguing that policy makers have private information about their objectives (which may be influenced by non-economic factors) that only affects economic outcomes through the policy choice and thus acts like a taste shifter. If so, the unconditional independence of policy rules assumed in the benchmark macro models would be violated. Time-varying preferences could be modeled with ϕ_π and ϕ_y as functions of FOMC composition over time.

5.2 Non-policy Parameters

Table 3 reports estimates of the models' non-policy parameters. Note that, unlike the Taylor Rule parameters, the NK and DSGE coefficients are not directly comparable due to substantial differences in the size and structural restrictions of the two models. Nevertheless, these coefficient estimates during the Great Moderation (column II) are generally consistent with the literature. In the NK model, the slope of the IS Curve (ψ) is negative and small in absolute value, implying a relatively high coefficient of relative risk aversion of about 50. The slope of the Phillips Curve (κ) and the expectations feedback are both positive and relatively high but significantly less than 1.0. The VAR and NK estimates of κ are very similar except during the Great Moderation (column II), where the NK slope is considerably more positive. In the DSGE model, there are too many parameters to discuss individually. However, these DSGE coefficient estimates, along with those in Period I, are roughly in line with what has been reported in Smets and Wouters (2007) and subsequent estimates of their model.

After the GFC, many of the estimated non-policy coefficients (column III) in the NK and DSGE models exhibit significant changes. Unlike the Taylor Rule coefficients, however, there was not a general reversion back to period-I values but rather heterogeneous breaks in a

dawala (2016), for examples. However, Debortoli and Nunes (2014) caution against interpreting structural shifts in the policy rule as simply a change in preferences, noting that shifts in the policy rule can obscure differences between factors inside and outside a policy maker's control.

variety of coefficients. In the NK model, the IS Curve slope (ψ) became more negative ($-.19$ versus $-.03$) and the coefficient of relative risk aversion fell to about 9 and the output gap is more sensitive to the real rate. The Phillips Curve slope (κ) declined considerably (.38 to .03), returning to its approximate value before the Great Moderation. Inflation expectations (β) also decreased somewhat (.91 to .82) but remained much closer to the rational benchmark (1.0) than before the Great Moderation.

In the DSGE model, several coefficients changed notably after the GFC.[24] Two long-run coefficients, steady state growth ($\overline{\gamma}$) and hours ($\bar{l}$), fell by economically and statistically significant amounts (.48 to .21 and .79 to -3.52, respectively). In contrast, steady state inflation ($\overline{\pi}$) essentially was unchanged. The capital share (α) declined by almost half and the external habit (λ) increased notably (.51 to .83). The DSGE model also provides an estimates the natural real interest rate as a function of the rate of time preference, β, and risk aversion, σ_c.[25] Estimates for periods I and II are larger than many in the literature but similar to the original estimates in Smets and Wouters (2007). In period III, the real rate estimates fell almost in half (3.1 to 1.7 percent). The remaining DSGE coefficients did not change statistically significantly.

Overall, the estimated changes in the DSGE coefficients, especially during Period III, reinforce the need for macro models to incorporate time variation to properly identify monetary policies. Steady state (trend) growth varied, perhaps due to breaks in productivity trends (e.g., Fernald 2014) and variation in the marginal product of capital. Our estimates of the (typically fixed) natural real interest rate (r) varied too, similarly to Del Negro et al (2019).[26] The benchmark models also assume a fixed inflation target, $\overline{\pi}$, inflation volatility

[24] The changes in DSGE estimates from Periods I to II are qualitatively consistent with the time variation in coefficients reported by Fernandez-Villaverde and Rubio-Rumirez (2007) for their roughly analogous sample.

[25] The natural real interest rate is calculated as in Smets and Wouters (2007): $\bar{r} = (\frac{\gamma^{\sigma_c}\Pi}{\beta} - 1)100$.

[26] As noted earlier, our estimates of the natural real interest rate are consistent with Smets and Wouters (2007) original estimate of r^* but are considerably higher than traditional estimates in the literature. Holston et al (2018) estimated the natural rate of interest to be close to zero after the financial crisis, and Del Negro et al (2019) estimate it to be slightly above one. Resolving these large inconsistencies around r^* is key to explaining structural breaks. Time-variation in the natural rate might follow Laubach and Williams (2003), whose natural real rate of interest, $r^* = (1/\sigma)\overline{\gamma} + \beta$, and its law of motion, $r_t^* = c\overline{\gamma}_t + z_t$, would be added to the Taylor Rule. Steady state growth varies over time ($\overline{\gamma}_t$) while z_t captures other determinants of r_t^*, such

during the Great Inflation and the subsequent "opportunistic disinflation" (Orphanides and Wilcox 2002) suggest the target also may be time varying. Our estimates of the slope of the NK Phillips Curve and degree of nominal price and wage stickiness changed, as in Kim et al. (2014) and Jorgenson and Lansing (2021), for examples, suggesting a need to model variation in the underlying related trends. Estimated increases in coefficients on inflation expectations may reflect increasing efficiency of monetary policy, including the embrace of anchoring of inflation to expectations, and transparency and cooperation with the private sector (Spencer et al. 2013). Finally, consumer risk aversion also declined, but it is hard to draw hard conclusions about the cause(s) given the challenges in estimating this parameter (Calvet et al. 2021).

5.3 Discussion

Evidence in this section suggests the presence of structural breaks in many coefficients. However, the analysis cannot verify econometrically whether the presence of UMP is responsible for the observed breaks without a clear alternative model that includes UMP, as discussed in Section **??**. Nevertheless, it is instructive to summarize the results thus far and assess whether they provide suggestive evidence of changes in monetary policy. Three comparisons offer useful information and perspective:

- *Parameter types* – The structural breaks occur in both Taylor Rule (policy) and non-policy coefficients. This finding makes it even more difficult to isolate the effects of omitted policies on the Taylor Rule. Because the policy and non-policy parameters are estimated jointly, changes in the latter can influence estimates of the former.

- *Subsamples* – Structural breaks after the Financial Crisis (from II-III) are not always consistent with breaks during the Great Moderation (from I-II). For some parameters, breaks are statistically significant in only one period while for others it is significant in

as household rate of time preference.

both (or neither). For some coefficients the breaks reverse sign from period II to period III, making the post-GFC coefficients similar to those before the Great Moderation, which is hard to explain.

- *Models* – Structural breaks are hard to compare between the parsimonious small models (VAR, NK) and the larger DSGE model. While none of the models includes UMP, the DSGE model has more variables that are likely to be influenced (directly or indirectly) by UMP. Thus, it is difficult to identify whether coefficient changes, especially non-policy, are due to omitted monetary policies or to changes in the private-sector economic structure.

Thus, the evidence presented thus far does not conclusively indicate whether UMP is responsible for the comprehensive and heterogeneous structural breaks in model parameters.

6 Additional Diagnostics

The previous section documents evidence of significant breaks in the individual parameters of the models. Motivated by the evidence, this section characterizes the collective effect of breaks in model parameters using three additional diagnostic measures: 1) estimated structural shocks; 2) dynamic responses to structural shocks; and 3) estimated DSGE output gaps. Changes in these measures reveal the macroeconomic implications of parameter breaks in period III, and providing supporting evidence of structural breaks and a fuller understanding of the nature of the observed changes.

6.1 Structural shocks

The time series characteristics of each model's estimated structural shocks provide one way to summarize the comprehensive impact of parameter breaks. Figure 3 plots the estimated monetary policy shocks for each model from the full sample and each subsample.[27] The

[27] See Figures 8 and 9 in the Appendix for plots of other structural shocks in the NK and DSGE models.

correlation of monetary shocks between models varies from .83 to .91 the full sample. For the subsamples, the correlations vary from .54 (the VAR:NK correlation in period II) to .90 (the NK:DSGE correlation in period III.)

The full-sample monetary shocks for periods I and II are familiar and similar across models. The variance is greatest in period I, but even larger during the period of reserves targeting (1980-1983). The variance declined significantly during the Great Moderation due to "better monetary policy", a phenomenon Stock and Watson (2002) and some others found to be the most influential cause of the Moderation. However, aside from some relatively modest fluctuations during the GFC recession, the full-sample monetary shock in period III did not exhibit another large change in variance (decrease or increase) following implementation of UMP.

The relative variances of the monetary shocks in each subsample also are instructive.[28] In period I, the subsample VAR and NK shocks are *more* volatile than the full-sample shock (ratios of 1.43 and 1.46, respectively), but the DSGE shock is much less variable (ratio of .35). While differences in shock variances across models are not surprising, the models exhibit heterogeneous changes in their shock variance ratios across subsamples as well. For the VAR and NK models, the monetary shock variance ratios in periods II and III (roughly .5 in both subsamples) are about one-third as large as in period I. In contrast, the DSGE monetary shock variance ratios in periods II and III (.13 and .39, respectively) are similar to period I. Thus, the DSGE monetary shock becomes three times more variable in period III but there is not much change in the volatility of the VAR and NK shocks.

The autoregressive properties of the monetary shocks also vary not only across models but also across subsamples within the models.[29] Persistence of the NK and DSGE monetary shocks generally increased in periods II and III, but the increase was statistically significant only in the DSGE model in period III (.31 to .54).

[28]See Table 4 in the Appendix for the full-sample standard deviations and the variance ratios for each subsample shock relative to its full-sample variance.

[29]See Table 5 in the Appendix for complete set of autoregressive parameters for each model and sample.

Changes in the time series properties of the estimated monetary shocks indirectly reflect the effects of changes in the estimated coefficients of Taylor Rule and non-policy structural equations reported in Section 5. While the estimated model coefficients exhibit various breaks, the time series properties of the monetary shocks in period III reveal moderate changes in variability and persistence. The changes are larger and more significant in the DSGE model (more variable and more persistent) perhaps because it contains more parameters and thus more opportunities to capture and interpret the breaks.[30]

6.2 Impulse Responses

Changes in the Taylor Rule and non-policy parameters also affect the dynamic properties of the macro models. Figure 4 shows impulse responses to a 100-basis-point shock to the federal funds rate for the full sample and each subsample; recall that the post-GFC period (III) uses $\widehat{i}_t$. These subsample impulse responses are unrestricted, allowing all policy and non-policy coefficients to change in each subsample.

The unrestricted responses are broadly consistent with prior evidence for each model and, with few exceptions, *qualitatively* similar across models and samples. Monetary tightening produces a familiar, modest decline in output and inflation, followed by a slow return to steady state for about 1-3 years. The funds rate paths are nearly the same, decaying slowly from 100 basis points in a similar fashion across models with only modest differences in the degree of persistence. This result is consistent with the finding in Carvahlo et al (2021) that different estimation methods provide largely unbiased impulse response functions, although estimation methods may vary in precision.

However, the output gap and inflation responses exhibit somewhat larger and more economically important *quantitative* differences across models and subsamples. For example, although the average output response is similar across models and samples, the absolute

[30]The time series properties of the other estimated NK and DSGE structural shocks also exhibit a variety of changes but there are too many to discuss here. See the Appendix for more details and discussion of these other shocks.

magnitude of output responses varies more across samples in the VAR and NK models than the DSGE model. Also, the DSGE has notably larger (in absolute value) and economically different inflation responses than the other models. In particular, the full sample responses are notably more muted for the NK model. Interestingly, no subsample response consistently matches the full-sample responses across models. A lack of consistency across models perhaps is to be expected given their different sizes and restrictions, but the relative inconsistency of subsample responses across models is striking. That is, the largest absolute response for each model is not associated with the same subsample.

Although subsample heterogeneity across responses may be providing additional evidence of structural breaks, most differences are economically moderate for at least two reasons. First, as noted in Section 6.1, the variances and persistence of the structural shocks change considerably across subsamples, which also impact the coefficient estimates. Unlike the monetary shock fixed at 100 basis points, impulse responses based on shocks' estimated standard deviations (not displayed but available upon request) vary much more. Second, data-consistent dynamics are the inherent goal of model estimation. Thus, while breaks in the economic structure may occur in some coefficients (e.g., the Taylor Rule), offsetting breaks in other parameters (e.g., non-policy) may occur simultaneously to maintain dynamic properties consistent with the data.

To better understand the effects of structural breaks in Taylor Rule parameters, we conducted a counterfactual exercise in which the non-policy parameters are held fixed at their full-sample estimates. Figure 5 shows impulse responses to a 100-basis point fed funds shock using models in which only Taylor Rule coefficients change across subsamples, thus better illustrating the effects of structural breaks in policy on model dynamics.[31]

The counterfactual responses reveal three important insights. First, absolute magnitudes are roughly two to three times larger than the unrestricted responses (Figure 4) for all but the DSGE inflation response, which is about the same. Second, the counterfactual responses

[31] Figures 5 and 6 exclude the VAR because its distinction between structure and reduced-form is less precise.

are much more consistent across subsamples with smaller qualitative differences. Third, the Great Moderation (period II) responses more consistently differ from the pre-Moderation (period I) and post-Crisis (period III) responses, which are similar to each other. The Great Moderation output and inflation responses are smaller (more negative) in the NK model, and vice versa for the DSGE model. Except for the Great Moderation response, the NK fed funds rate responses exhibit a short-lived amplification after the shock while the DSGE responses do not. Overall, these counterfactual responses show that breaks in the non-policy parameters mute the volatility of responses differing only in Taylor Rules. Changes in Taylor Rule coefficients across samples and models thus have limited effects on model dynamics.

For completeness, Figure 6 shows impulse responses to a 100-basis point fed funds shock for the converse counterfactual exercise. The Taylor Rule coefficients are held fixed at their full-sample estimates and only non-policy parameters change across subsamples, thus better illustrating the effects of changes in non-policy coefficients on model dynamics. The fixed-policy counterfactual responses of output and inflation also are larger (more negative) than the unrestricted responses, but not as much as when holding the non-policy coefficients fixed. Variation in non-policy coefficients holding the Taylor Rule fixed also produces more heterogeneous responses across subsamples, but the heterogeneity is not economically large.

To summarize the dynamics results, changes in model coefficients have modest economic effects on dynamics when all coefficients are allowed change. Changes in subsets of the coefficients alter dynamic responses by magnitudes that are larger and economically more important, but these effects largely offset when all model coefficients are allowed to change.

6.3 Output Gaps

Figure 7 plots the DSGE output gaps for all samples along with the CBO output gap for comparison. Unlike the CBO output gap, changes in model coefficients across subsamples influence the estimated DSGE output gap and cause discontinuities across subsamples. The full-sample DSGE and CBO gaps are positively correlated and have comparable levels until about 1970. After that the DSGE gap diverges by many percentage points and becomes very persistent, rarely crossing zero. The magnitude of divergence is economically meaningful for monetary policy responses to output gaps in the Taylor Rule for all models. The divergence also may be a concern for construction and interpretation of the two gaps.[32]

Figure 7 shows the DSGE output gap exhibits economically significant breaks across subsamples. The period-I and full-sample DSGE gaps are similar, and both are fairly close to the CBO gap. During the Great Moderation, however, the period-II DSGE gap is roughly 3-5 percentage points below the full-sample DSGE gap and crosses zero multiple times. After the GFC, the period-III and full-sample DSGE output gaps are about the same magnitude again and follow a similar U-shaped path. However, the period-III DSGE gap returns to zero faster and arrives there by 2020 like the CBO gap. In contrast, the full-sample DSGE gap is still around -4 percent. This discrepancy has major implications for the determination of optimal monetary (and fiscal) policy during the COVID-19 recession and recovery.

Subsample breaks in the DSGE output gap provide complementary evidence of structural breaks in the DSGE model coefficients. The results in Section 5 suggest that changes in long-run coefficients like the steady-state growth rate likely play an important role, but changes in coefficients associated with wage-price block and Taylor Rule may also contribute. Alternatively, the results in this subsection may reflect the impact of the omission of explicit UMP in the macro model equations. Either way, failure to allow for structural breaks in model coefficients appears to lead to bias in the estimated full-sample DSGE output gap for long periods.

7 Explaining Structural Breaks

Economically and statistically significant structural breaks in both Taylor Rule *and* non-policy coefficients makes inference about cause(s) of the breaks much more difficult. If breaks

[32]The original DSGE gap in Smets and Wouters (2007) was estimated through 2004 and corresponds more closely the CBO gap. See the Appendix for more details.

had occurred only in the Taylor Rule, it might be possible to discern shifts due to UMP using the shadow rate as an approximate control. However, with many key non-policy coefficients exhibiting economically significant time variation in point estimates and variances, it does not appear feasible to identify breaks induced by UMP separately from breaks unrelated to policy in the benchmark models. Thus, the benchmark macro models may be exhibiting structural breaks in parameters that actually reflect some or all of these sources of time variation rather than breaks associated with UMP.

If so, then a substantially more complex macro model(s) is needed to account for the observed time variation. The work of Fernandez-Villaverde and Rubio-Ramirez (2007, 2010) is an important step in this direction and good launching point for introducing time variation. However, even that work does not include all sources of observed non-policy structural breaks discussed earlier, and it does not include any elements of UMP. Incorporating all or even some of these extensions and estimating the expanded models is a challenging task that is beyond the scope of the current paper.

Ultimately, future research will need to address the omission of UMP and by explicitly specifying the policy rule(s) governing UMP and its transmission to non-policy structure. During and after the GFC, the Federal Reserve implemented a wide range of UMP that can be classified into three broad categories: 1) Forward Guidance (FG); 2) Quantitative Easing and Tightening (QE/QT); and 3) expanded liquidity facilities (ELF).[33] These new policies and tools are absent from the benchmark macro models and thus may require modification of the Taylor Rule and/or addition of variables and structural equations (including new policy rules) to properly capture the effects of UMP.

Forward Guidance (FG) – Developed during the (relatively) low-interest rate period of the early 2000s, FG was tested first during the subsequent increase of the federal funds rate in 2004 (Gürkaynak, et al., 2004). The main implementation of FG occurred during the GFC when the federal funds rate hit the ZLB for six years. Rather than using the shadow funds

[33] For more details of these policies, see https://www.federalreserve.gov/monetarypolicy/policytools.htm.

rate, it may be necessary to insert the prototypical FG model (equation 4) into the benchmark macro models. Richer specifications of the term structure and expectation formation also may be needed to identify the effects of UMP properly.

Quantitative Easing (QE) – From 2008-2014, the Fed substantially expanded its Open Market Operations (OMO) to conduct large-scale asset purchases (LSAP) of: 1) mortgage-backed securities, to ease bank risk and lower mortgage rates; and 2) longer term Treasury bonds, to increase maturity and lower long-term risk-free rates. This QE strategy added a new monetary policy governing the conduct and objective(s) of LSAPs (and eventually sales, or LSAS). One manifestation of QE policy is a simple balance sheet rule(s) that emulates the Taylor formula, such as those proposed in Sims and Wu (2021), Sims et al (2021), and Dean (2021):

$$B_t = \rho_B B_{t-1} + (1 - \rho_B)[\theta_\pi(\pi_t - \pi^*) + \theta_x x_t] + \nu_t \tag{14}$$

where B_t is the Fed's holding of long-term bonds.[34] Dean (2021) also adds a term structure equation to the model.

The other manifestation is a target(s) and rule(s) for Fed mortgage and/or Treasury real bond holdings and related long-term interest rates. While the Fed does not explicitly announce a target long-term rate, the balance sheet rule implicitly suggests one. In Carlstrom et al (2017), the Taylor Rule for the short rate becomes:

$$i_t = \rho i_{t-1} + (1 - \rho)[\phi_\pi(\pi_t - \pi^*) + \phi_x x_t) + \phi_{tp} tp_t] + \epsilon_t^{MP} \tag{15}$$

where tp_t is the term premium. Most likely, macro models need to introduce explicit specifications of QE policies and asset-pricing equation(s) to identify the effects of UMP properly.[35]

[34] In practice, the FOMC appears to implement such a rule as *changes* in Fed's target purchases of QE securities. See the regular FOMC statements during and after the two recent periods of ZLB (2008-2015 and 2020-2022) for details.

[35] Modeling UMP became even more challenging in 2020 with two new responses to the COVID-19 pandemic: 1) expanded QE that included purchases of investment-grade corporate bonds via the Secondary Market Corporate Credit Facility (SMCCF) and short-term state and local government notes via the Municipal Liquidity Facility (MLF); and 2) new direct lending to small and medium-sized businesses via the Paycheck Protection Program Liquidity Facility (PPPLF) and the Main Street Lending Program.

Expanded Liquidity Facilities (ELF) – During and after the Financial Crisis, the Fed developed new policy tools to provide liquidity and improve functioning of financial markets. One type includes new short-term rates: 1) interest on excess reserves (IOER), which was replaced by interest on reserve balances (IORB) in 2021 after required reserves were eliminated; and 2) interest rates on overnight reverse repurchase agreements (ONRRP), a form of OMO. It is unclear whether more than one short-term rate is needed in the benchmark macro models, but Dudley (2021) argued that IORB should replace fed funds as the policy instrument. More research is needed to understand relationships among the short-term rates and the fed funds target range, especially how liquidity shortages emerge and cause financial instabilities that spill over into the real economy. Because IORB is the price that clears the market for bank (excess) reserves, it also is closely related to QE policies. A second type of new liquidity tool includes a variety of facilities that provide liquidity directly to banks, borrowers, and investors in key credit markets – some of which have expired.[36] These other facilities are mainly relevant during liquidity crises and the Fed has demonstrated a willingness to start and stop facilities as needed. Introduction of such intermittent policy tools may also be needed in macro models but seems particularly challenging to specify.

To recap, observed structural breaks in the Taylor Rule may reflect the effects of omitting variables and equations associated with UMP. If so, expanding the macro models to incorporate the UMP and related non-policy equations may be necessary to fully and properly capture the effects of UMP. Recent research is developing theoretical foundations for some types of UMP.[37] However, no theoretical model includes all elements of UMP, and there is little or no estimation of such models. Addressing these deficiencies is important for future research.

[36] See https://www.federalreserve.gov/monetarypolicy/policytools.htm

[37] Examples include Gertler and Karadi (2013), Hagedorn et al. (2019), and Sims and Wu (2021); Dean (2021) adds average inflation targeting (AIT).

8 Conclusions

Three classes of benchmark macroeconomic models exhibit economically and statistically significant breaks in their Taylor Rule and non-policy coefficients after 2007:Q3. Evidence of breaks is stronger and more widespread in the larger DSGE model. The main result pertaining to the Taylor rule is a decline in the strength of the Fed's response to inflation relative to its response to output, making the Taylor Rule somewhat more similar to its form in the period before the Great Moderation. A structural break(s) was likely given the implementation of UMP that are not included explicitly in the benchmark models. However, it is unclear whether these widespread and heterogeneous breaks reflect the effects of UMP or something else. And, perhaps surprisingly, using a shadow rate to control for UMP and avoid the ZLB does not alter the estimation outcomes much.

The observed structural breaks are heterogeneous and challenging to interpret well. One complicating factor is that breaks in non-policy coefficients influence the models as much or more than breaks in the Taylor Rule coefficients. Thus, many elements of the benchmark models may be susceptible to time variation that is not included in them. The first important task is to build and estimate a macro model(s) that incorporate some or all of the time-varying elements that are clouding inference about the effects of UMP. Then testing the revised model for structural breaks is more likely to identify the effects of UMP.

A second complicating factor is that the benchmark macro models do not include explicit specifications of UMP. Consequently, the observed structural breaks may be simply reflecting the estimation effects of omitted variables (and equations) rather than UMP. A form of the Lucas Critique (1978) also may be at work. After controlling for potential time-variation in macro models, the obvious remedy is to include explicit specifications of FG (augmented Taylor Rule or more), QE, and possibly ELF into the model(s). Testing for structural breaks in the revised model's non-policy block of equations should more effectively identify the effects of the introduction of UMP.

Neither the task of controlling for time-variation in macro models nor the task of introducing explicit UMP instruments and rules is easy or fast. However, both are potentially important directions for future research and analysis of modern monetary policy.

9 Tables and Figures

Figure 1: The Wu-Xia Shadow Rate and the Fed's bond holdings

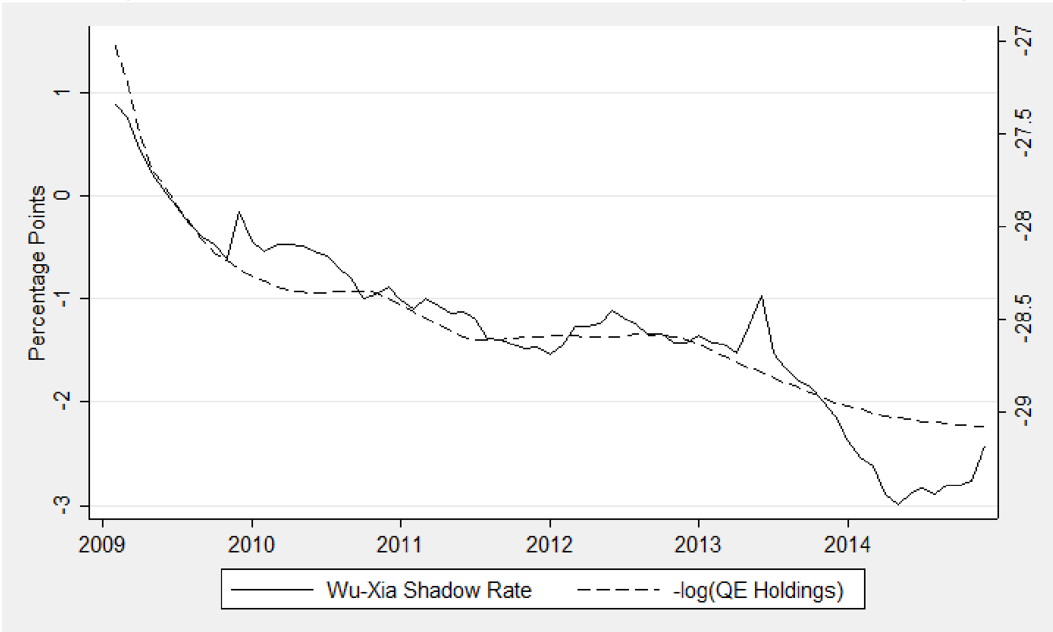

Figure 2: P-value from endogenous breakpoint Chow test

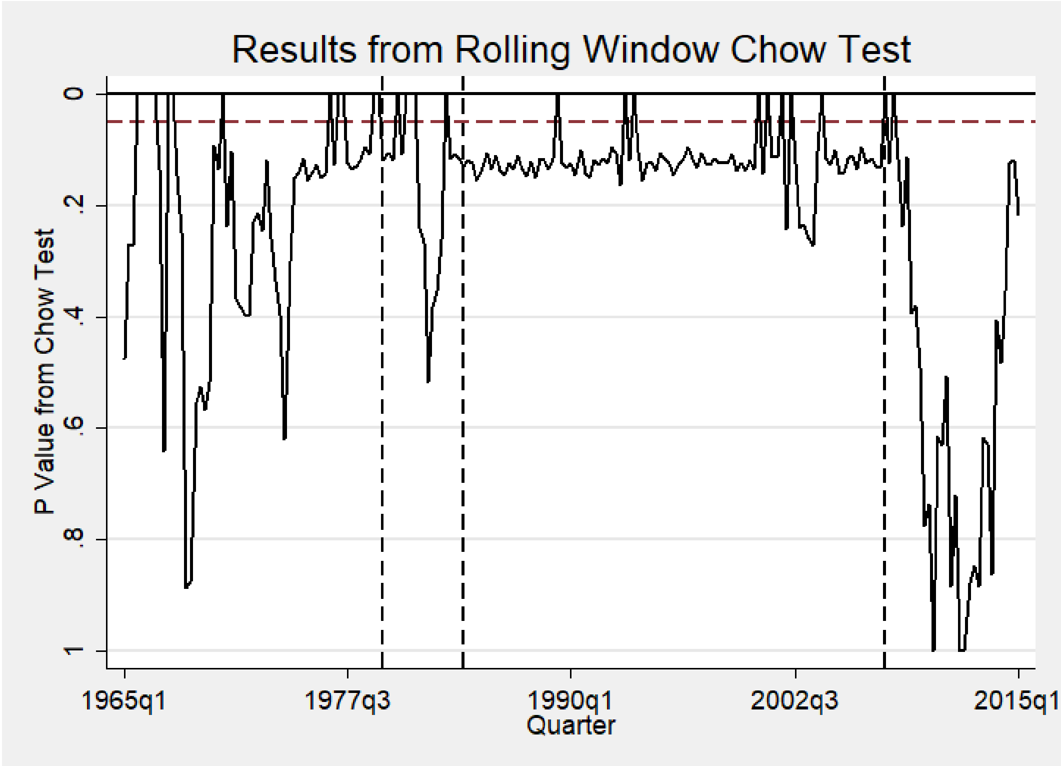

Figure 3: Structural monetary shocks by model and sample

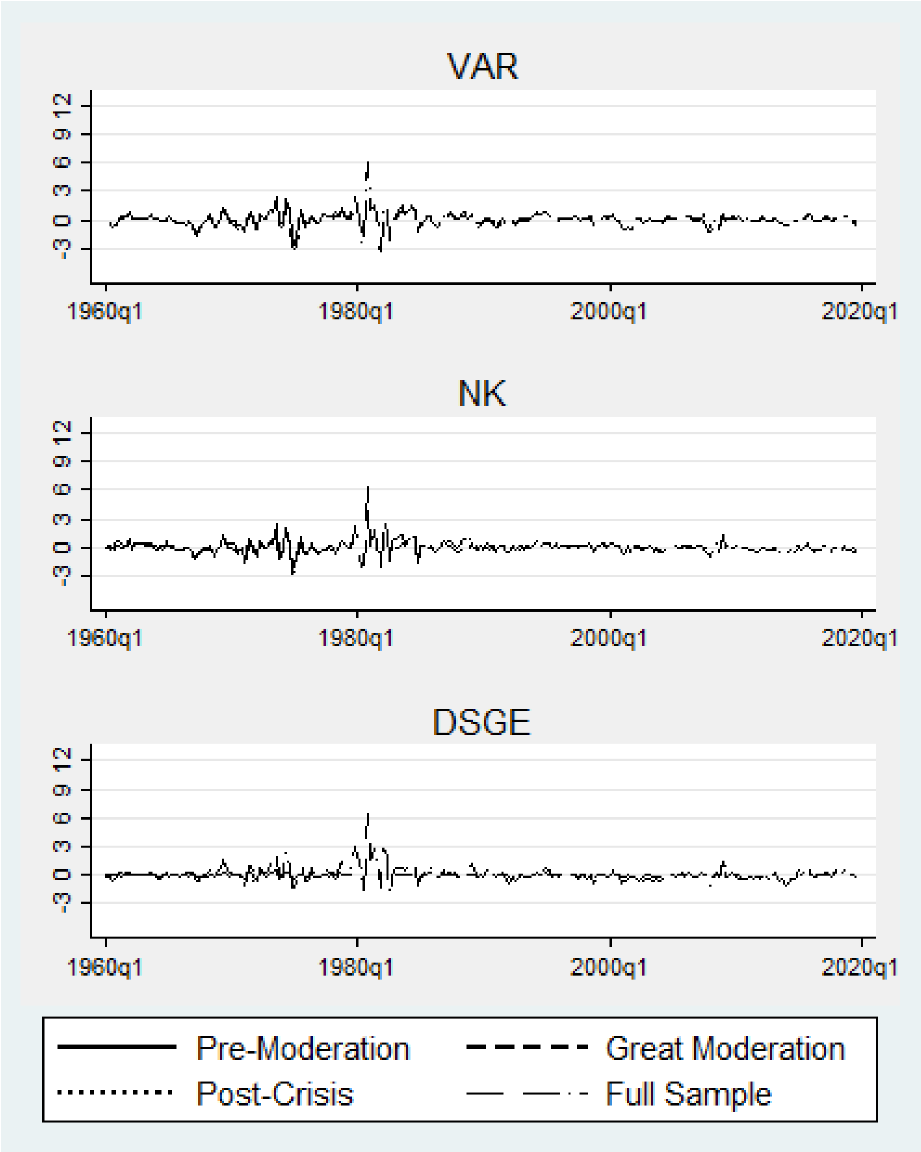

Figure 4: Impulse response to a 100bp monetary shock by model and sample

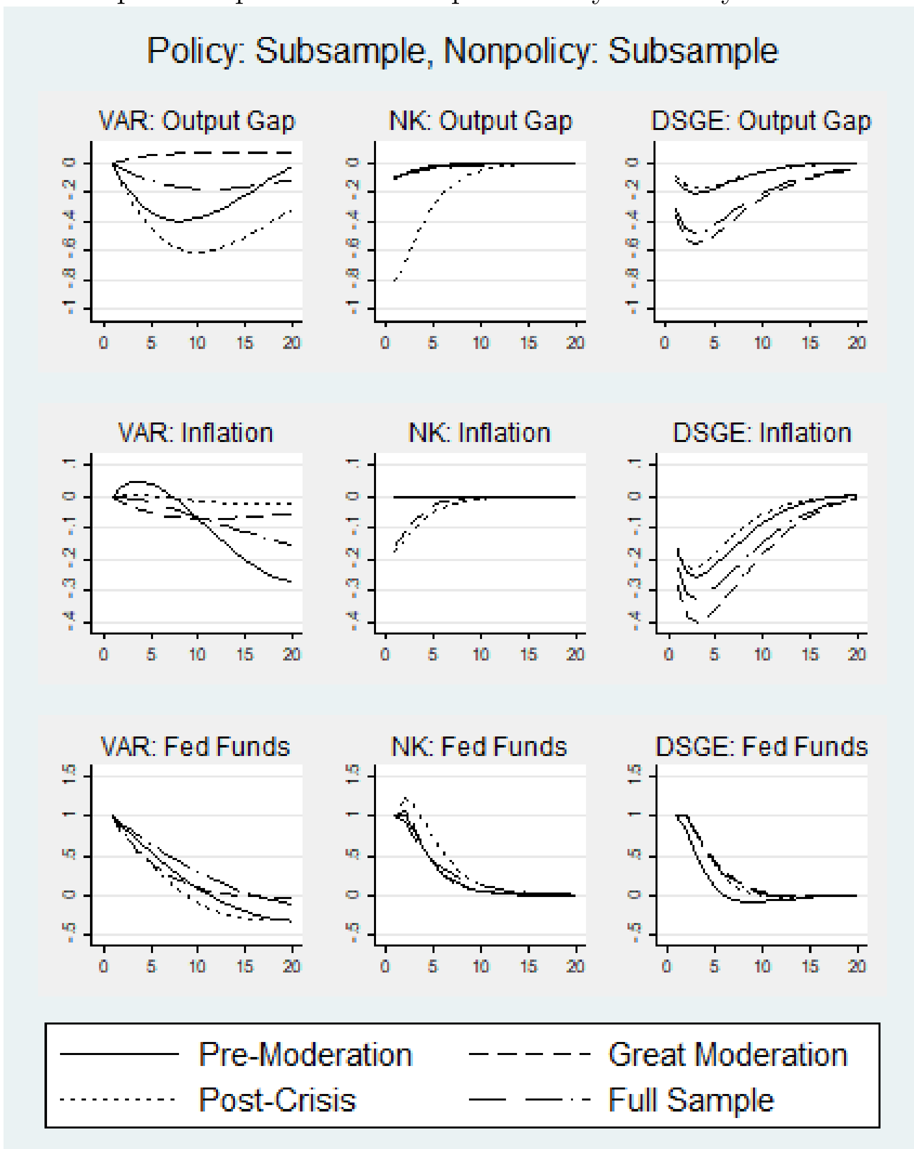

Figure 5: Counterfactual responses to a 100bp monetary shock by model and sample

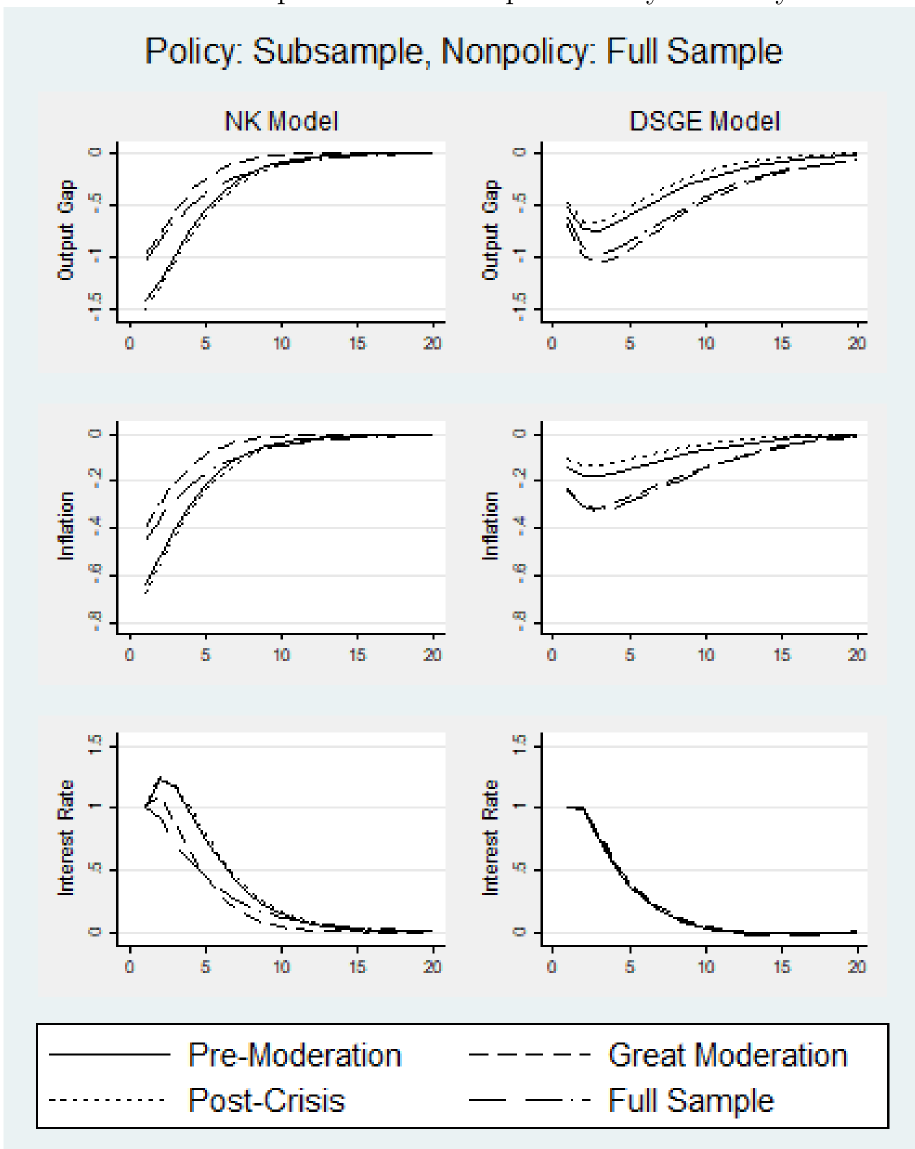

Figure 6: Counterfactual responses to a 100bp monetary shock by model and sample

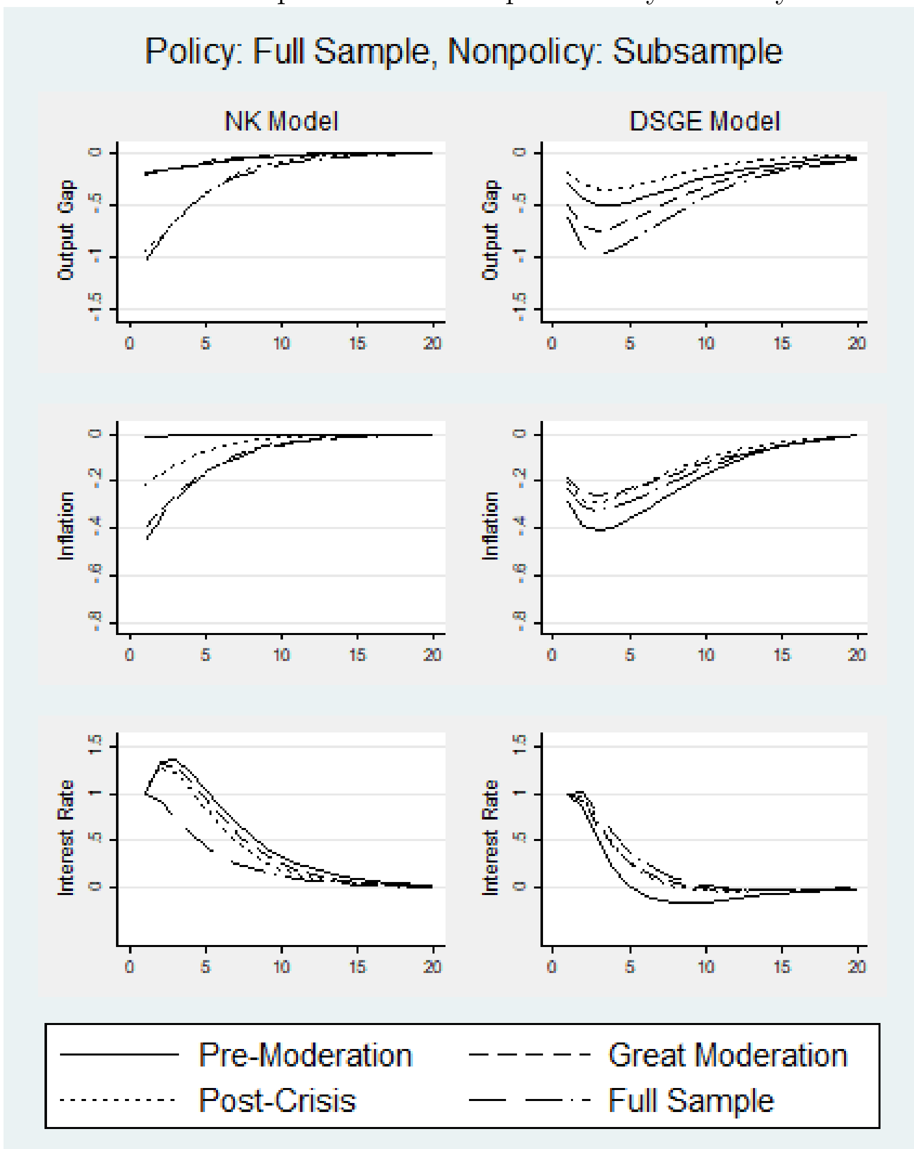

Figure 7: Estimated Output Gaps

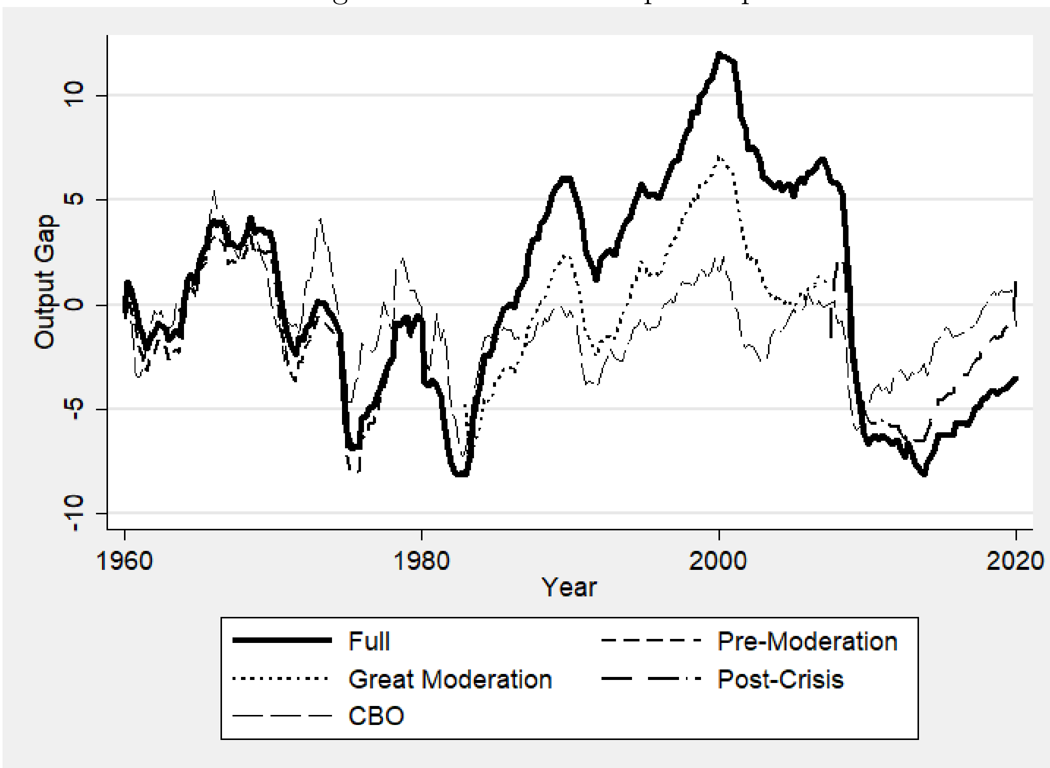

Table 1: Summary of structural break literature

Paper	Sample	Break(s)	Taylor Rule Implications	Nonpolicy Implications
Estrella and Fuhrer (2003)	1966-1997	early-1980s	backward looking models are more stable than forward looking	NA
Duffy and Engle-Warnick (2006)	1955-2003	1980	$\downarrow \phi_y$	NA
Bernanke and Mihov (1998)	1965-1996	1979 & 1982	no policy variable captures monetary policy	NA
Clarida et al. (2000)	1960-1996	1979	$\uparrow \phi_\pi, \uparrow \phi_y$	Taylor Rule induces determinacy
Smets and Wouters (2007)	1954-2007	early-1980s	$\uparrow \phi_\pi, \downarrow \phi_y$	More flexible prices
Canova (2009)	1955-2002	1982	$\uparrow \phi_\pi$	Flatter IS Curve
Castelnuovo (2012)	1966-2007	1970s	Including M2 improves fit before 1970s	Omission of M2 produces distorted IRFs
Ilbas (2012)	1966-2005	early-1980s	$\uparrow \phi_r, \uparrow \phi_\pi$	Lower inflation target
Fernández-Villaverde and Rubio-Ramírez (2007)	1955-2000	NA	Parameters tend to drift over time	Drift in pricing parameters correlates with inflation
Bunzel and Enders (2010)	1965-2007	early-1980s	$\uparrow \phi_r, \uparrow \phi_\pi$	NA
Coibion and Gorodnichenko (2011)	1960-2002	early-1980s	$\uparrow \phi_\pi, \uparrow \phi_{\Delta y}, \downarrow \phi_y$	Lower trend inflation
Sims and Zha (2006)	1959-2003	late-1970s, mid-1980s	$\downarrow$ variance of ϕ_π, ϕ_y	NA
Primiceri (2005)	1953-2001	early-1980s	$\downarrow$ variance of $\phi_\pi, \phi_y, \uparrow \phi_\pi$	NA
Mavroeidis (2010)	1961-2006	1979	TR cannot be accurately estimated after 1979	NA
Dean and Schuh	1960-2020	1984, 2008	1984: $\uparrow \phi_\pi$, 2008: $\downarrow \phi_\pi, \phi_y$	Flatter Phillips Curve, lower trend growth

Table 2: Taylor Rule estimates by subsample and model

	Parameter Estimates						Changes		
	Parameter	Full	I	II	III$\hat{i}$	IIIi	I-II	II-III$\hat{i}$	II-IIIi
VAR	ϕ_π	3.55	1.43	2.67	-1.61	.24	1.24	-4.28***	-2.43**
		(1.61)	(1.51)	(1.23)	(1.77)	(.89)			
	ϕ_y	4.05	1.26	3.10	1.64	1.37	1.84**	-1.43***	-1.73***
		(.68)	(1.03)	(.45)	(.50)	(.06)			
	ρ	.91	.83	.83	.86	.81	.00	.03	-.02
		(.02)	(.07)	(.04)	(.03)	(.04)			
NK	ϕ_π	1.37	1.27	2.41	1.31	1.13	1.14	-1.1	-1.28
		[1.16,1.62]	[1.00,1.47]	[2.30,2.55]	[1.00,1.57]	[1.02,1.24]			
	ϕ_y	.99	.85	.69	.64	.87	-.16	-.05	.18
		[.75,1.26]	[.62,1.06]	[.43,.99]	[.38,.93]	[.70,1.06]			
	ρ	.79	.63	.62	.78	.56	-.01	.16	.06
		[.70,.88]	[.50,.74]	[.54,.68]	[.68,.88]	[.53,.59]			
DSGE	ϕ_π	1.99	1.48	1.97	1.42	1.44	.49	-.55	-.53
		[1.57,2.41]	[1.26,1.69]	[1.58,2.36]	[1.27,1.57]	[1.09,1.77]			
	ϕ_y	.30	.15	.09	.21	.13	-.06	.12	.04
		[.25,.34]	[.09,.20]	[.02,.17]	[.14,.28]	[.08,.18]			
	ρ	.86	.80	.84	.75	.83	.04	-.09	.01
		[.82,.89]	[.74,.87]	[.79,.88]	[.65,.86]	[.76,.91]			
	$\phi_{\Delta y}$	.41	.17	.16	.20	.16	-.01	.04	0
		[.37,.44]	[.13,.22]	[.11,.21]	[.12,.27]	[.11,.22]			

Note: VAR estimates report the standard errors, and the NK and DSGE models report the 90% HPD confidence interval. The VAR is estimated using OLS. The NK and DSGE are estimated with Bayesian methods using priors consistent with those used in previous estimations. The IIIi estimation is estimated using the occasionally binding constraint method described in Cuba-Borda et al. (2019) and Giovannini, Pfeiffer, and Ratto (2021).

Table 3: Structural Estimates from New Keynesian and Bayesian DSGE Model

Parameter Output								Change		
	Parameter	Parameter Role	Full	I	II	III$\hat{i}$	IIIi	I-II Change	II-III$\hat{i}$ Change	II-IIIi Change
VAR	κ	Phillips Curve	.01 (.03)	-.01 (.04)	-.02 (.04)	.13 (.05)	.12 (.04)	.02	.15***	.14***
NK	ψ	IS Curve	-.02 [-.03,-.01]	-.07 [-.12,-.01]	-.03 [-.06,-.01]	-.19 [-.38,-.01]	-.51 [-.66,-.36]	.04	-.16	.32
	κ	Phillips Curve	.02 [.01,.03]	.02 [.01,.03]	.38 [.32,.42]	.03 [.01,.04]	1.64 [1.42,1.89]	.36	-.35	1.26
	β	Inflation feedback	.70 [.61,.79]	.69 [.53,.87]	.91 [.87,.95]	.82 [.61,.99]	.93 [.83,.96]	.22	-.09	.02
DSGE	$100(\beta^{-1}-1)$	Time Preference	.25 [.16,.34]	.18 [.07,.30]	.17 [.06,.29]	.23 [.09,.37]	.19 [.07,.28]	-.01	.06	.01
	$\bar{\pi}$	Steady State Inflation	.65 [.55,.73]	.70 [.51,.86]	.68 [.56,.84]	.65 [.53,.78]	.61 [.51,.71]	-.02	-.03	-.07
	$\bar{\gamma}$	Steady State Growth	.33 [.28,.36]	.27 [.17,.38]	.48 [.42,.53]	.21 [.16,.27]	.22 [.17,.27]	.21	-.27	-.26
	$\bar{l}$	Steady State Hours	-1.94 [-3.41,-.54]	2.72 [1.28,4.33]	.79 [-1.36,2.46]	-3.52 [-4.76,-2.38]	-4.00 [-5.16,-2.34]	-1.93	-4.31	-4.79
	ρ	Investment Adjustment	7.95 [6.04,9.55]	4.70 [3.11,6.19]	6.38 [4.14,8.66]	6.31 [4.28,8.13]	5.50 [3.18,7.38]	1.68	-.07	-.88
	σ_c	Risk Aversion	1.53 [1.22,1.83]	1.64 [1.25,1.98]	1.25 [.81,1.75]	.93 [.72,1.13]	1.10 [.74,1.43]	-.39	-.32	-.15
	λ	External Habit Degree	.74 [.68,.80]	.67 [.60,.75]	.52 [.39,.67]	.82 [.76,.89]	.63 [.50,.75]	-.15	.30	.10
	ξ_w	Calvo: Wages	.93 [.91,.95]	.75 [.67,.83]	.69 [.52,.89]	.73 [.63,.89]	.82 [.74,.91]	-.06	.04	.13
	σ_l	Frisch Elasticity	2.62 [1.75,3.31]	1.97 [1.09,3.09]	2.20 [1.16,3.37]	.97 [.25,1.75]	1.15 [.25,1.84]	.23	-1.23	-1.05
	ξ_p	Calvo: Prices	.83 [.80,.87]	.55 [.50,.60]	.81 [.74,.88]	.71 [.60,.83]	.73 [.61,.86]	.26	-.1	-.08
	ι_w	Wage Indexation	.72 [.62,.82]	.48 [.28,.67]	.46 [.17,.74]	.41 [.17,.65]	.37 [.16,.56]	-.02	-.05	-.09
	ι_p	Price Indexation	.20 [.10,.32]	.37 [.16,.62]	.35 [.12,.60]	.33 [.13,.52]	.30 [.12,.48]	-.02	-.02	-.05
	ψ	Capacity Utilization Cost	.55 [.42,.69]	.28 [.12,.42]	.68 [.46,.88]	.71 [.54,.91]	.74 [.59,.91]	.4	.03	.06
	Φ	Fixed Cost Share	1.69 [1.59,1.80]	1.55 [1.40,1.68]	1.53 [1.32,1.70]	1.42 [1.27,1.57]	1.36 [1.21,1.51]	-.02	-.11	-.17
	α	Capital Share	.22 [.20,.25]	.24 [.19,.28]	.21 [.15,.26]	.12 [.07,.16]	.13 [.09,.17]	-.03	-.09	-.08
	r^*	Real Interest Rate	3.04	2.50	3.09	1.71	1.74	.59	-1.38	-1.35

Note: VAR estimates report the standard errors, and the NK and DSGE models report the 90% HPD confidence interval. The VAR is estimated using OLS. The NK and DSGE are estimated with Bayesian methods using priors consistent with those used in previous estimations. The IIIi estimation is estimated using the occasionally binding constraint method described in Cuba-Borda et al. (2019) and Giovannini, Pfeiffer, and Ratto (2021).

References

[1] Afonso, G., Kim, K., Martin, A., Nosal, E., Potter, S., and Schulhofer-Wohl, S. Monetary policy implementation with an ample supply of reserves. Tech. rep., FEDS Working Paper, 2020.

[2] Barnichon, R., and Mesters, G. The phillips multiplier. *Journal of Monetary Economics 117* (2021), 689–705.

[3] Bauer, M., and Rudebusch, G. D. The signaling channel for federal reserve bond purchases. *International Journal of Central Banking* (2014).

[4] Benati, L. Drift and breaks in labor productivity. *Journal of Economic Dynamics and Control 31*, 8 (2007), 2847–2877.

[5] Benhabib, J., Schmitt-Grohé, S., and Uribe, M. Monetary policy and multiple equilibria. *American Economic Review 91*, 1 (2001), 167–186.

[6] Benhabib, J., Schmitt-Grohé, S., and Uribe, M. Avoiding liquidity traps. *Journal of Political Economy 110*, 3 (2002), 535–563.

[7] Bernanke, B. S., and Mihov, I. Measuring monetary policy. *The Quarterly Journal of Economics 113*, 3 (1998), 869–902.

[8] Bilbiie, F. O. Optimal forward guidance. *American Economic Journal: Macroeconomics 11*, 4 (2019), 310–45.

[9] Bordo, M. D., and Istrefi, K. Perceived fomc: the making of hawks, doves and swingers. Tech. rep., National Bureau of Economic Research, 2018.

[10] Brayton, F., Laubach, T., Reifschneider, D. L., et al. The FRB/US model: A tool for macroeconomic policy analysis. Tech. rep., Board of Governors of the Federal Reserve System), 2014.

[11] Bundick, B., and Smith, A. L. The dynamic effects of forward guidance shocks. *Review of Economics and Statistics* (2016), 1–45.

[12] Bunzel, H., and Enders, W. The taylor rule and "opportunistic" monetary policy. *Journal of Money, Credit and Banking 42*, 5 (2010), 931–949.

[13] Calvet, L. E., Campbell, J. Y., Gomes, F., and Sodini, P. The cross-section of household preferences. Tech. rep., National Bureau of Economic Research, 2021.

[14] Campbell, J. R., Evans, C. L., Fisher, J. D., Justiniano, A., Calomiris, C. W., and Woodford, M. Macroeconomic effects of federal reserve forward guidance [with comments and discussion]. *Brookings papers on economic activity* (2012), 1–80.

[15] Campbell, J. R., Fisher, J. D., Justiniano, A., and Melosi, L. Forward guidance and macroeconomic outcomes since the financial crisis. *NBER Macroeconomics Annual 31*, 1 (2017), 283–357.

[16] Canova, F. What explains the great moderation in the us? a structural analysis. *Journal of the European Economic Association 7*, 4 (2009), 697–721.

[17] Carvalho, C., Nechio, F., and Tristao, T. Taylor rule estimation by ols. *Journal of Monetary Economics 124* (2021), 140–154.

[18] Castelnuovo, E. Estimating the evolution of money's role in the us monetary business cycle. *Journal of Money, Credit and Banking 44*, 1 (2012), 23–52.

[19] Chung, H. T., Kiley, M. T., and Laforte, J.-P. Documentation of the Estimated, Dynamic, Optimization-based (EDO model of the U.S. economy: 2010 version. Finance and Economics Discussion Series 2010-29, Board of Governors of the Federal Reserve System, 2010.

[20] Clarida, R., Gali, J., and Gertler, M. The science of monetary policy: a new keynesian perspective. *Journal of Economic Literature 37*, 4 (1999), 1661–1707.

[21] Clarida, R., Gali, J., and Gertler, M. Monetary policy rules and macroeconomic stability: Evidence and some theory. *The Quarterly Journal of Economics 115*, 1 (2000), 147–180.

[22] Coibion, O., and Gorodnichenko, Y. Monetary policy, trend inflation, and the great moderation: An alternative interpretation. *American Economic Review 101*, 1 (2011), 341–70.

[23] Coibion, O., and Gorodnichenko, Y. Why are target interest rate changes so persistent? *American Economic Journal: Macroeconomics 4*, 4 (2012), 126–62.

[24] Cole, S. J. Learning and the effectiveness of central bank forward guidance. *Journal of Money, Credit and Banking 53*, 1 (2021), 157–200.

[25] Cole, S. J., and Martínez-García, E. The effect of central bank credibility on forward guidance in an estimated new keynesian model. *Available at SSRN 3495757* (2019).

[26] Cuba-Borda, P., Guerrieri, L., Iacoviello, M., and Zhong, M. Likelihood evaluation of models with occasionally binding constraints. *Journal of Applied Econometrics 34*, 7 (2019), 1073–1085.

[27] Dean, J. Better on average? average inflation targeting with unconventional monetary policy.

[28] Debortoli, D., and Nunes, R. Monetary regime switches and central bank preferences. *Journal of Money, credit and Banking 46*, 8 (2014), 1591–1626.

[29] Del Negro, M., Giannone, D., Giannoni, M. P., and Tambalotti, A. Global trends in interest rates. *Journal of International Economics 118* (2019), 248–262.

[30] Del Negro, M., Giannoni, M. P., and Patterson, C. The forward guidance puzzle. *FRB of New York Staff Report*, 574 (2012).

[31] Duffy, J., and Engle-Warnick, J. Multiple regimes in us monetary policy? a nonparametric approach. *Journal of Money, Credit and Banking* (2006), 1363–1377.

[32] Estrella, A., and Fuhrer, J. C. Monetary policy shifts and the stability of monetary policy models. *Review of Economics and Statistics 85*, 1 (2003), 94–104.

[33] Fernández-Villaverde, J., and Rubio-Ramírez, J. Macroeconomics and volatility: Data, models, and estimation. Tech. rep., National Bureau of Economic Research, 2010.

[34] Fernández-Villaverde, J., Rubio-Ramírez, J. F., Cogley, T., and Schorfheide, F. How structural are structural parameters?[with comments and discussion]. *NBER Macroeconomics Annual 22* (2007), 83–167.

[35] Fuhrer, J. Expectations as a source of macroeconomic persistence: Evidence from survey expectations in a dynamic macro model. *Journal of Monetary Economics 86* (2017), 22–35.

[36] Fuhrer, J. C., and Madigan, B. F. Monetary policy when interest rates are bounded at zero. *Review of Economics and Statistics 79*, 4 (1997), 573–585.

[37] Fuhrer, J. C., Moore, G. R., and Schuh, S. D. Estimating the linear-quadratic inventory model maximum likelihood versus generalized method of moments. *Journal of Monetary Economics 35*, 1 (1995), 115–157.

[38] Gertler, M., and Karadi, P. Qe 1 vs. 2 vs. 3...: A framework for analyzing large-scale asset purchases as a monetary policy tool. *29th issue (January 2013) of the International Journal of Central Banking* (2018).

[39] Giovannini, M., Pfeiffer, P., and Ratto, M. Efficient and robust inference of models with occasionally binding constraints. Tech. rep., JRC Working Papers in Economics and Finance, 2021.

[40] Gonzalez-Astudillo, M. Identifying the stance of monetary policy at the zero lower bound: A markov-switching estimation exploiting monetary-fiscal policy interdependence. *Journal of Money, Credit and Banking 50*, 1 (2018), 115–154.

[41] Guerrieri, L., and Iacoviello, M. Occbin: A toolkit for solving dynamic models with occasionally binding constraints easily. *Journal of Monetary Economics 70* (2015), 22–38.

[42] Gürkaynak, R. S., Sack, B. P., and Swanson, E. T. Do actions speak louder than words? the response of asset prices to monetary policy actions and statements. *The Response of Asset Prices to Monetary Policy Actions and Statements (November 2004)* (2004).

[43] Hagedorn, M., Luo, J., Manovskii, I., and Mitman, K. Forward guidance. *Journal of Monetary Economics 102* (2019), 1–23.

[44] Hirose, Y., and Inoue, A. The zero lower bound and parameter bias in an estimated dsge model. *Journal of Applied Econometrics 31*, 4 (2016), 630–651.

[45] Holston, K., Laubach, T., and Williams, J. C. Measuring the natural rate of interest: International trends and determinants. *Journal of International Economics 108* (2017), S59–S75.

[46] Ihrig, J. E., Senyuz, Z., and Weinbach, G. C. The fed's "ample-reserves" approach to implementing monetary policy. Tech. rep., FEDS Working Paper, 2020.

[47] Ilbas, P. Revealing the preferences of the us federal reserve. *Journal of Applied Econometrics 27*, 3 (2012), 440–473.

[48] Ireland, P. N. A method for taking models to the data. *Journal of Economic Dynamics and Control 28*, 6 (2004), 1205–1226.

[49] Jorgensen, P. L., and Lansing, K. J. Anchored inflation expectations and the slope of the phillips curve. Federal Reserve Bank of San Francisco.

[50] Joyce, M., Miles, D., Scott, A., and Vayanos, D. Quantitative easing and unconventional monetary policy–an introduction. *The Economic Journal 122*, 564 (2012), F271–F288.

[51] Kim, C.-j., Manopimoke, P., and Nelson, C. R. Trend inflation and the nature of structural breaks in the new keynesian phillips curve. *Journal of Money, Credit and Banking 46*, 2-3 (2014), 253–266.

[52] Kocherlakota, N. R. Practical policy evaluation. *Journal of Monetary Economics 102* (2019), 29–45.

[53] Krippner, L. Measuring the stance of monetary policy in zero lower bound environments. *Economics Letters 118*, 1 (2013), 135–138.

[54] Lakdawala, A. Changes in federal reserve preferences. *Journal of Economic Dynamics and Control 70* (2016), 124–143.

[55] Laubach, T., and Williams, J. C. Measuring the natural rate of interest. *Review of Economics and Statistics 85*, 4 (2003), 1063–1070.

[56] Lindé, J., Smets, F., and Wouters, R. Challenges for central banks' macro models. In *Handbook of macroeconomics*, vol. 2. Elsevier, 2016, pp. 2185–2262.

[57] Lucas, R. J. Econometric policy evaluation: A critique. *Carnegie-Rochester Conference Series on Public Policy 1*, 1 (January 1976), 19–46.

[58] Lütkepohl, H. *Introduction to multiple time series analysis.* Springer Science & Business Media, 2013.

[59] Mavroeidis, S. Monetary policy rules and macroeconomic stability: Some new evidence. *American Economic Review 100*, 1 (2010), 491–503.

[60] McCallum, B. T., et al. Theoretical analysis regarding a zero lower bound on nominal interest rates. *Journal of Money, Credit and Banking 32*, 4 (2000), 870–904.

[61] McKay, A., Nakamura, E., and Steinsson, J. The power of forward guidance revisited. *American Economic Review 106*, 10 (2016), 3133–58.

[62] Oehlert, G. W. A note on the delta method. *The American Statistician 46*, 1 (1992), 27–29.

[63] Orphanides, A., and Wilcox, D. W. The opportunistic approach to disinflation. *International finance 5*, 1 (2002), 47–71.

[64] Primiceri, G. E. Time varying structural vector autoregressions and monetary policy. *The Review of Economic Studies 72*, 3 (2005), 821–852.

[65] Rossi, B. Identifying and estimating the effects of unconventional monetary policy: How to do it and what have we learned? *The Econometrics Journal 24*, 1 (2021), C1–C32.

[66] Schmitt-Grohe, S., Uribe, M., et al. The perils of taylor rules. *Journal of Economic Theory 96*, 1 (2001), 40–69.

[67] Shackleton, R., et al. Estimating and projecting potential output using cbo's forecasting growth model: Working paper 2018-03. Tech. rep., 2018.

[68] Shapiro, A. H., and Wilson, D. Taking the fed at its word: A new approach to estimating central bank objectives using text analysis. *Federal Reserve Bank of San Francisco* (2019).

[69] Sims, C. A. Interpreting the macroeconomic time series facts: The effects of monetary policy. *European Economic Review 36*, 5 (1992), 975–1000.

[70] Sims, C. A., and Zha, T. Were there regime switches in us monetary policy? *American Economic Review 96*, 1 (2006), 54–81.

[71] Sims, E., and Wu, J. C. Evaluating central banks' tool kit: Past, present, and future. *Journal of Monetary Economics 118* (2021), 135–160.

[72] Sims, E., Wu, J. C., and Zhang, J. The four equation new keynesian model. *The Review of Economics and Statistics* (2021), 1–45.

[73] Smets, F., and Wouters, R. Shocks and frictions in us business cycles: A bayesian dsge approach. *American Economic Review 97*, 3 (2007), 586–606.

[74] Spencer, R. W., Huston, J. H., and Hsie, E. G. The evolution of federal reserve transparency under greenspan and bernanke. *Eastern Economic Journal 39*, 4 (2013), 530–546.

[75] Stock, J. H., and Watson, M. W. Has the business cycle changed and why? *NBER macroeconomics annual 17* (2002), 159–218.

[76] Svensson, L. E. What rule for the federal reserve? forecast targeting. Tech. rep., National Bureau of Economic Research, 2017.

[77] Swanson, E. T., and Williams, J. C. Measuring the effect of the zero lower bound on medium-and longer-term interest rates. *American Economic Review 104*, 10 (2014), 3154–85.

[78] Taylor, J. B. Discretion versus policy rules in practice. In *Carnegie-Rochester Conference Series on Public Policy* (1993), vol. 39, Elsevier, pp. 195–214.

[79] Taylor, J. B. Simple monetary rules: many strengths and few weaknesses. *European Journal of Law and Economics* (2021), 1–17.

[80] West, K. D., and Wilcox, D. W. A comparison of alternative instrumental variables estimators of a dynamic linear model. *Journal of Business & Economic Statistics 14*, 3 (1996), 281–293.

[81] Wu, J. C., and Xia, F. D. Measuring the macroeconomic impact of monetary policy at the zero lower bound. *Journal of Money, Credit and Banking 48*, 2-3 (2016), 253–291.

[82] Wu, J. C., and Zhang, J. A shadow rate new keynesian model. *Journal of Economic Dynamics and Control 107* (2019), 103728.

Online Appendix

A Bayesian Estimation Priors

The prior distributions, means, and standard deviations used in estimation, given in Table A1, are similar to those used in Canova (2009) for the NK model. The slope of the IS curve, ψ, and Phillips Curve, κ, have gamma distributions with a prior mean of -.5 and 1, respectively. The inflation feedback parameter, β, has a beta distribution and a prior mean near a rational expectations benchmark at .98. The monetary parameters are set at $\rho = .8, \phi_y = .5$ and $\phi_\pi = 1.3$. Additionally, the prior for the inflation parameter, ϕ_π is truncated at 1 to not allow indeterminacy.

For the DSGE model, we use the same priors as Smets and Wouters (2007), given in Table A2. The time preference rate is set at 0.25 (corresponding to $\beta = .9975$), the steady state inflation ($\bar{\pi}$) and growth rate ($\bar{\gamma}$) are set at 0.62 and and .4, respectively (corresponding to an annualized 2.5% inflation rate and 1.6% real growth rate). Steady state hours, $\bar{l}$, is set at 0, Firsh elasticity, σ_l, is 2, while risk aversion, σ_c, and habit formation, λ, are set at 1.5 and .7, respectively. The Calvo parameters, ξ_p and ξ_w, are both .5, and wage and price indexation, (ι_p, ι_w) are also .5. Finally, capacity utilization, ψ, is set at .5, and the fixed cost and capital shares (Φ and α) are 1.25 and .3, respectively. The monetary autoregressive parameter, ρ, is set at .75, and the monetary feedback parameters, $\phi_\pi, \phi_y, \phi_{\Delta y}$ are set at 1.5, .12, and .12, respectively, Similar to the NK model, the prior for ϕ_π is truncated at 1 to require determinacy.

B Additional Diagnostics

This section reports and discusses results of additional diagnostic analyses for model estimation not included in Section 6.

B.1 Non-monetary Structural Shocks

The monetary structural shocks for the NK and DSGE models are shown in Figure 3 of Section 6. Here, Figure B2 and Figure B3 plot the non-monetary structural shocks from the NK (η) and DSGE models (ε). In addition to the model parameters, the shock structure is highly variable between periods. The variance ratios of the shocks can be found in Table B1, and the autocorrelations are in Table B2.

For the NK model, the relative variance of the output gap shock is larger than its full sample estimate in period I. It declines from the period I and period II (from 1.42 to .61), but increases substantially to 3.30 times the full sample shock variance in the final subperiod. On the other hand, the inflation shock is similarly unstable between periods I and II (1.36 and 1.63 times the full sample variance, respectively), but is considerably *more* stable in period III (.88 times the full sample variance), when inflation was more stable. The output gap shock's persistence is largely stable between the Great Moderation and post-Crisis, shifting from .79 to .87. Meanwhile, The inflation shock is highly persistent and near unity in periods I and II. However, the persistence declines substantially in period III (from .99 to .65), corresponding to the lower variance in the inflation shock.

For the DSGE model, the shock structure is similarly unstable between subperiods. The productivity, risk premium, spending, investment, and price markup shocks each have a higher variance in period I than their full-sample estimates, varying from 2.19 (risk premium) to 1.11 (spending). Each then declines between period I and period II with the risk premium shock declining the most (from 2.19 to .76) and the spending shock declining the least (from 1.11 to .85). The wage markup shock has a lower variance in period I than its full sample estimate (.48), and the variance of the wage markup shock increases between periods I and II (to .80). The DSGE model struggles to fit period III, as only the variance of the spending shock declines between periods II and III, declining from .85 to .64. The relative variance of the productivity and investment shocks increases the least (both from .78 to .95), while the relative variance of the wage markup shock increases the most (from .80 to 1.77). Only the persistence of the productivity and wage markup shocks decline between periods I and II (from .99 to .92 and from .94 to .78, respectively). The persistence of the spending shock increases the least (from .90 to .96) and the persistence of the risk premium shock increases the most (from .24 to .74). Alternatively, between periods II and III, only the risk premium shock becomes more persistent (from .74 to .79). While each remaining shock's persistence declines in period III, the wage markup shock declines the most, from .78 to .21.

B.2 Non-Monetary Impulse Responses

The main text focuses on the responses of the benchmark models to innovations in the monetary policy shock, which is common to all three models and directly relevant to the Taylor Rule. We do not include impulse responses to the other structural shocks here for two reasons. The non-monetary shocks are not easily compared across models and the sheer number of responses requires too much textual discussion. However, the full set of impulse responses is available upon request.

B.3 Output Gaps

Extending the sample for the DSGE model from Smets and Wouter's (2007) original estimation (red line ending in 2004) to our sample period (blue line ending in 2019) drastically changes the DSGE output gap, as shown in Figure B1. The original DSGE gap (red line) is close to the CBO gap until the mid-1970s, when it fell well below the CBO gap before catching up to the CBO gap in the late 1980s. Adding 15 more years of data to the estimation largely resolves the discrepancy in the 1970s and 1980s. However, it introduces a new, even larger discrepancy between the DSGE and CBO gaps from the late 1980s through 2019 as noted in the main text.

Figure B1: Original versus Updated DSGE Output Gaps

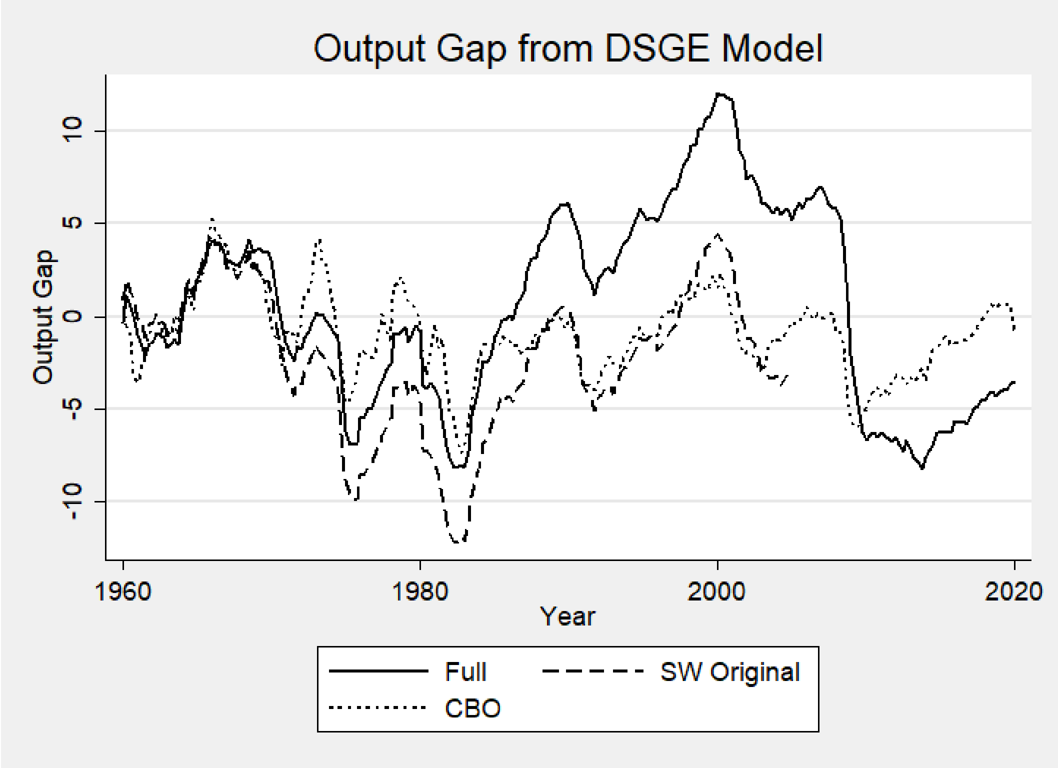

Figure B2: Structural shocks (η) from NK model

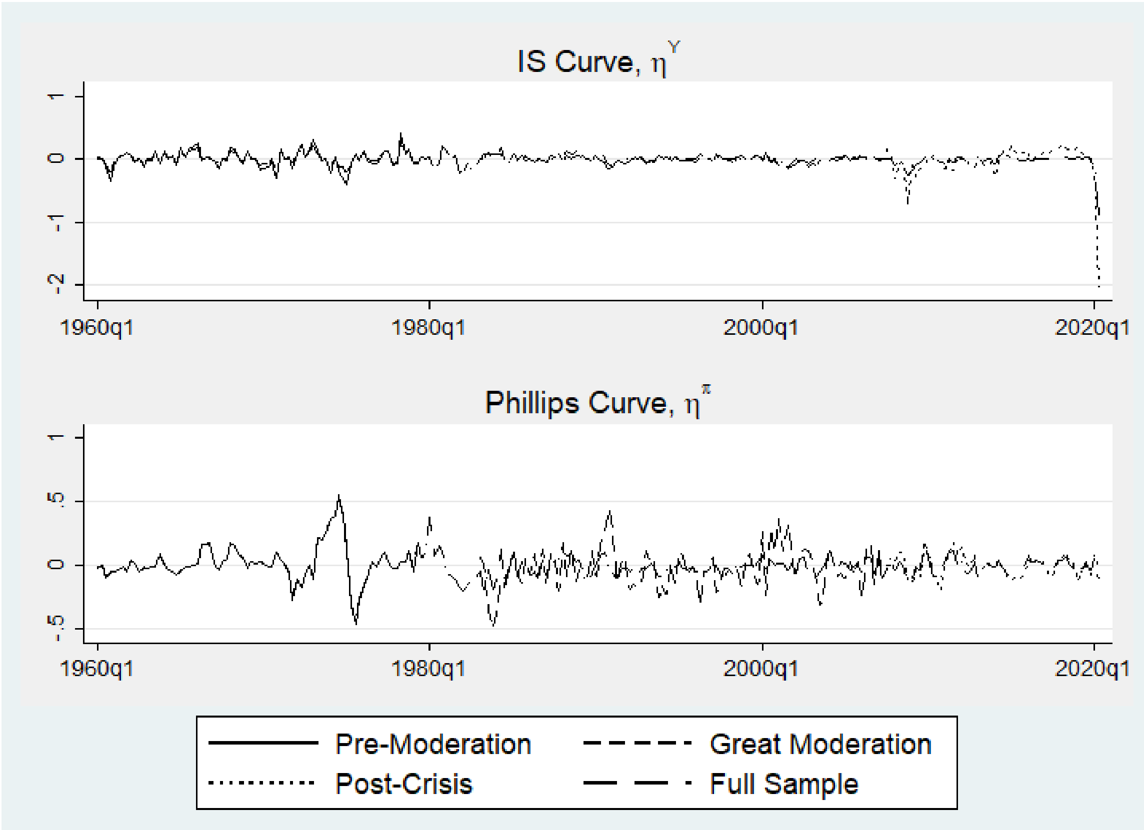

Figure B3: Structural shocks (ε) from DSGE model

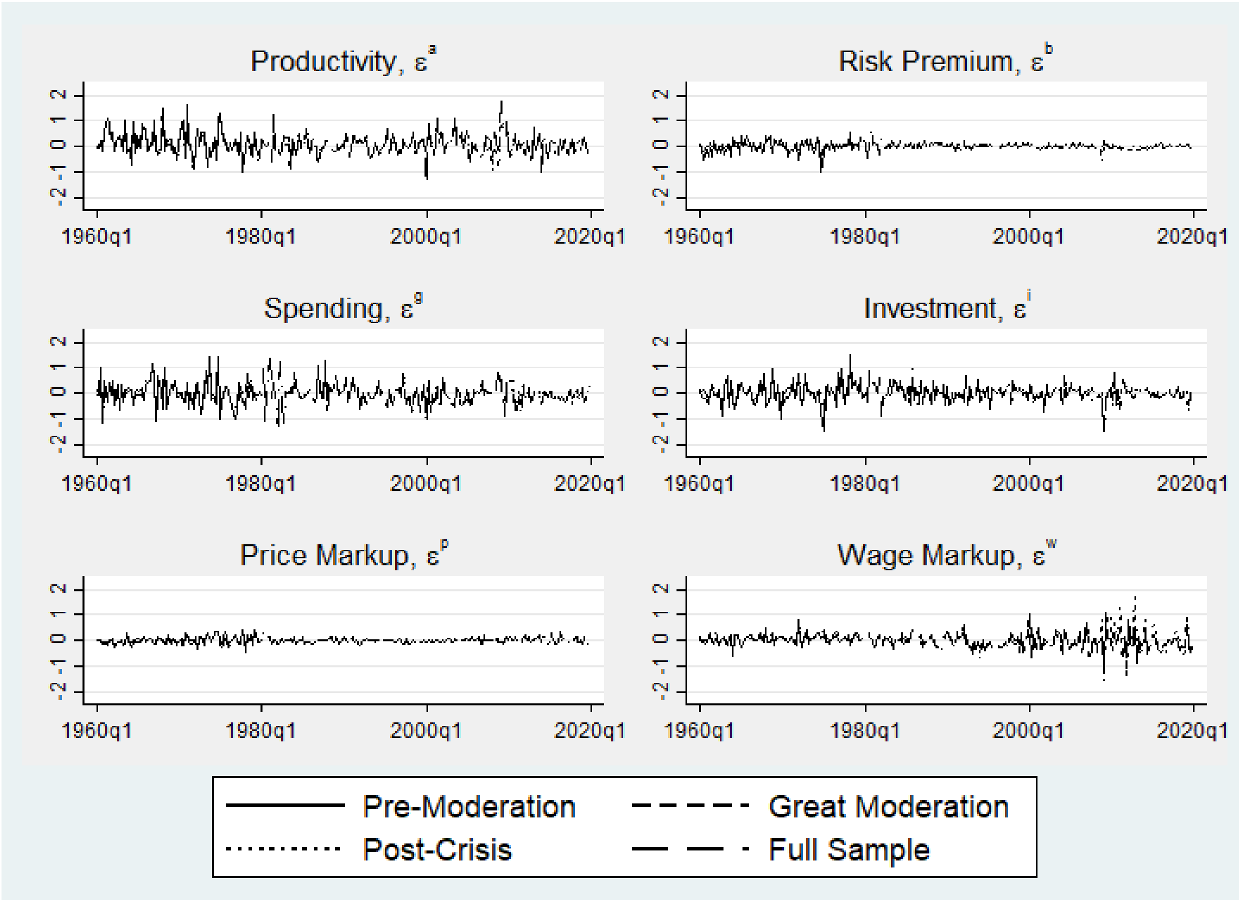

Table A1: Estimation priors

Model	Parameter	Parameter Role	Prior Distribution	Prior Mean
NK	ψ	IS curve slope	Gamma	-.50 (.35)
	κ	Phillips Curve slope	Gamma	1.00 (2.00)
	β	Inflation Expectation feedback	Beta	.98 (.05)
	ρ	Monetary smoothing	Beta	.8 (.25)
	ϕ_π	Taylor Rule: Inflation	Normal	1.3 (.5)
	ϕ_y	Taylor Rule: Output	Beta	.5 (.25)

Table A2: Estimation priors

Model	Parameter	Parameter Role	Prior Distribution	Prior Mean
DSGE	$100(\beta^{-1}-1)$	Time Preference Rate	Gamma	.25 (.10)
	$\bar{\pi}$	Steady State Inflation	Gamma	.62 (.10)
	$\bar{\gamma}$	Steady State Growth Rate	Normal	.40 (.10)
	$\bar{l}$	Steady State Hours	Normal	.00 (2.00)
	ρ	Investment Adjustment Cost	Normal	4.00 (1.50)
	σ_c	Risk Aversion	Normal	1.50 (.37)
	λ	External Habit Degree	Beta	.70 (.10)
	ξ_w	Calvo Parameter: Wages	Beta	.50 (.10)
	σ_l	Frisch Elasticity	Normal	2.00 (.75)
	ξ_p	Calvo Parameter: Prices	Beta	.50 (.10)
	ι_w	Indexation to Past Wages	Beta	.50 (.15)
	ι_p	Indexation to Past Prices	Beta	.50 (.15)
	ψ	Capacity Utilization Cost	Beta	.50 (.15)
	Φ	Fixed Cost Share	Normal	1.25 (.12)
	α	Capital Share	Normal	.30 (.05)
	ρ	Monetary smoothing	Beta	.75 (.1)
	ϕ_π	Taylor Rule: Inflation	Normal	1.5 (.25)
	ϕ_y	Taylor Rule: Output	Normal	.12 (.05)
	$\phi_{\Delta y}$	Taylor Rule: Growth	Normal	.12 (.05)

Table B1: Structural shock standard deviation

Model	Parameter	Role	FS	Ratio to FS		
				I	II	III
VAR	σ_t^y	Output Gap	.74 (.03)	1.25	.62	.78
	σ_t^π	Inflation	.31 (.01)	1.28	.63	.58
	σ_t^i	Monetary	.78 (.04)	1.43	.52	.41
NK	η_t^y	Output Gap	.10 [.06,.13]	1.42	.61	3.30
	η_t^π	Inflation	.11 [.08,.14]	1.36	1.63	.88
	η_t^i	Monetary	.80 [.74,.87]	.95	.50	.29
DSGE	ϵ_t^a	Productivity	.47 [.44,.51]	1.22	.78	.95
	ϵ_t^b	Risk Premium	.12 [.11,.13]	2.19	.76	1.13
	ϵ_t^g	Spending	.47 [.44,.50]	1.11	.85	.64
	ϵ_t^i	Investment	.40 [.34,.46]	1.20	.78	.95
	ϵ_t^m	Monetary	.85 [.78,.90]	.22	.14	.40
	ϵ_t^p	Price Markup	.14 [.13,.16]	1.21	.58	1.07
	ϵ_t^w	Wage Markup	.36 [.32,.39]	.48	.80	1.77

Table B2: Structural shock persistence

Model	Parameter	Parameter Role	Full	I	II	III	I-II Change	II-III Change
NK	ρ_Y	Output Gap Shock	.92 [.88,.95]	.90 [.84,.96]	.79 [.74,.85]	.87 [.78,.99]	-.11	.08
	ρ_π	Inflation Shock	.99 [.98,.99]	.99 [.97,.99]	.99 [.99,.99]	.65 [.42,.84]	0	-.34
	ρ_i	Monetary Shock	.34 [.13,.53]	.49 [.34,.64]	.60 [.42,.72]	.51 [.25,.81]	.11	-.09
DSGE	ρ_a	Productivity Shock	.99 [.99,.99]	.99 [.98,.99]	.92 [.87,.98]	.84 [.78,.91]	-.07	-.08
	ρ_b	Risk Premium Shock	.94 [.92,.95]	.24 [.07,.42]	.74 [.22,.93]	.79 [.72,.86]	.50	.05
	ρ_g	Spending Shock	.96 [.94,.98]	.90 [.84,.95]	.96 [.94,.99]	.78 [.63,.93]	.06	-.18
	ρ_i	Investment Shock	.72 [.64,.82]	.61 [.47,.78]	.70 [.55,.84]	.58 [.31,.82]	.09	-.12
	ρ_r	Monetary Shock	.14 [.05,.21]	.29 [.13,.45]	.31 [.13,.51]	.51 [.33,.68]	.02	.2
	ρ_p	Price Markup Shock	.93 [.89,.97]	.65 [.29,.99]	.75 [.55,.93]	.55 [.31,.81]	.10	-.2
	ρ_w	Wage Markup Shock	.30 [.16,.45]	.94 [.89,.99]	.78 [.50,.97]	.21 [.04,.37]	-.16	-.55

The VAR's shock persistence is simply the autoregressive parameter from each equation in the model.