

Taylor, John B.; Wieland, Volker

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Surprising comparative properties of monetary models: Results from a new model database

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EUROPEAN CENTRAL BANK

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NO 1261 / NOVEMBER 2010

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COMPARATIVE
PROPERTIES OF
MONETARY MODELS

RESULTS FROM
A NEW MODEL
DATABASE**

by John B. Taylor
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SURPRISING COMPARATIVE PROPERTIES OF MONETARY MODELS

RESULTS FROM A NEW MODEL DATABASE¹

by John B. Taylor² and Volker Wieland³



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¹ John B. Taylor is Mary and Robert Raymond Professor of Economics at Stanford University and George P. Shultz Senior Fellow in Economics at Stanford's Hoover Institution. Volker Wieland is Professor for Monetary Theory and Policy at Goethe University of Frankfurt. Wieland is grateful for financial support by a Willem Duisenberg Research Fellowship at the European Central Bank while this research project was initiated. Excellent research assistance was provided by Elena Afanasyeva, Tobias Cwik and Maik Wolters from Goethe University Frankfurt. Wieland acknowledges research assistance funding from European Community grant MONFISPOL under grant agreement SSH-CT-2009-225149. Comments by Mark Watson, Frank Smets, three anonymous referees and session participants at the AEA Meetings 2009, the German Economic Association Monetary Committee Meeting 2009, and the NBER Summer Institute 2009 Monetary Economics Group also proved very helpful. All remaining errors are our own.

² Herbert Hoover Memorial Building, Stanford University, Stanford, CA 94305, U.S.A.

³ House of Finance, Goethe University of Frankfurt, Grueneburgplatz 1, D-60323 Frankfurt am Main, Germany, wieland@wiwi.uni-frankfurt.de

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Address

Kaiserstrasse 29
60311 Frankfurt am Main, Germany

Postal address

Postfach 16 03 19
60066 Frankfurt am Main, Germany

Telephone

+49 69 1344 0

Internet

<http://www.ecb.europa.eu>

Fax

+49 69 1344 6000

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Abstract

In this paper we investigate the comparative properties of empirically-estimated monetary models of the U.S. economy. We make use of a new database of models designed for such investigations. We focus on three representative models: the Christiano, Eichenbaum, Evans (2005) model, the Smets and Wouters (2007) model, and the Taylor (1993a) model. Although the three models differ in terms of structure, estimation method, sample period, and data vintage, we find surprisingly similar economic impacts of unanticipated changes in the federal funds rate. However, the optimal monetary policy rules are different in the different models. Simple model-specific policy rules that include the lagged interest rate, inflation and current and lagged output gaps are not robust. Some degree of robustness can be recovered by using rules without interest-rate smoothing or with GDP growth deviations from trend in place of the output gap. However, improvement vis-à-vis other models, comes at the cost of significant performance deterioration in the original model. Model averaging offers a much more effective strategy for improving the robustness of policy rules.

Non technical summary

In our view it is important for research progress to document and compare these models and assess the value of model improvements in terms of the objectives of monetary policy evaluation. Keeping track of the different models is also important for monetary policy in practice because by checking the robustness of policy in different models one can better assess policy.

With these model comparison and robustness goals in mind we have recently created a new “monetary model database,” an interactive collection of models that can be simulated, optimized, and compared. The monetary model database can be used for model comparison projects and policy robustness exercises. Perhaps because of the large number of models and the time and cost of bringing modellers together, there have not been many model comparison projects and robustness exercises in recent years. In fact the most recent policy robustness exercise, which we both participated in, occurred 10 years ago as part of an NBER conference.

In this paper we focus on studying the comparative properties of empirically-estimated monetary models of the U.S. economy. We consider three representative models: the Christiano, Eichenbaum, Evans (2005) model, the Smets and Wouters (2007) model, and the Taylor (1993a) model. The model comparison and robustness analysis reveals some surprising results. Even though the two more recent models differ from the Taylor (1993a) model in terms of economic structure, estimation method, data sample and data vintage, they imply almost identical estimates of the response of U.S. GDP to an unexpected change in the federal funds rate, that is, to a monetary policy shock. This result is particular surprising in light of earlier findings by Levin, Wieland and Williams (1999, 2003) indicating that a number of models built after Taylor (1993a) exhibit quite different estimates of the impact of a monetary policy shock and the monetary transmission mechanism.

However, the optimal monetary policy rules are different in the different models. Simple model-specific policy rules that include the lagged interest rate, inflation and current and lagged output gaps are not robust. Some degree of robustness can be recovered by using rules without interest-rate smoothing or with GDP growth deviations from trend in place of the output gap. However, improvement vis-à-vis other models, comes at the cost of significant performance deterioration in the original model. Model averaging offers a much more effective strategy for improving the robustness of policy rules. Hence, using a model database, such as the one described in this paper, one can derive policy rules that are more robust to model uncertainty than those obtained with a single preferred model.

1. Introduction

Ever since the 1970s revolution in macroeconomics, monetary economists have been building quantitative models that incorporate the fundamental ideas of the Lucas critique, time inconsistency, and forward-looking expectations, in order to evaluate monetary policy more effectively. The common characteristic of these monetary models, compared with earlier models, is the combination of rational expectations, staggered price and wage setting, and policy rules, all of which have proved essential to policy evaluation.

Over the years the number of monetary models with these characteristics has grown rapidly as the ideas have been applied in more countries, as researchers have endeavoured to improve on existing models by building new ones, and as more data shed light on the monetary transmission process. The last decade, in particular, has witnessed a surge of macroeconomic model building as researchers have further developed the microeconomic foundations of monetary models and applied new estimation methods. In our view it is important for research progress to document and compare these models and assess the value of model improvements in terms of the objectives of monetary policy evaluation. Keeping track of the different models is also important for monetary policy in practice because by checking the robustness of policy in different models one can better assess policy.

With these model comparison and robustness goals in mind we have recently created a new “monetary model database,” an interactive collection of models that can be simulated, optimized, and compared. The monetary model database can be used for model comparison projects and policy robustness exercises. Perhaps because of the large number of models and the time and cost of bringing modellers together, there have not been many model comparison projects and robustness exercises in recent years. In fact the most recent policy robustness exercise, which we both participated in, occurred 10 years ago as part of an NBER

conference.¹ Our monetary model base provides a new platform that makes model comparison much easier than in the past and allows individual researchers easy access to a wide variety of macroeconomic models and a standard set of relevant benchmarks.² We hope in particular that many central banks will participate and benefit from this effort as a means of getting feedback on model development efforts.

This paper investigates the implications of three well-known models included in the model database for monetary policy in the U.S. economy. The first model, which is a multi-country model of the G-7 economies built more than fifteen years ago, has been used extensively in the earlier model comparison projects. It is described in detail in Taylor (1993a). The other two models are the best known representatives of the most recent generation of empirically estimated new Keynesian models, the Christiano, Eichenbaum and Evans (2005) model of the United States and the Smets and Wouters (2007) model of the United States.

The latter two models incorporate the most recent methodological advances in terms of modelling the implications of optimizing behavior of households and firms. They also utilize new estimation methods. The Christiano, Eichenbaum and Evans (2005) model is estimated to fit the dynamic responses of key macroeconomic variables to a monetary policy shock identified with a structural vector autoregression. The Smets and Wouters (2007) model is estimated with Bayesian methods to fit the dynamic properties of a range of key variables in response to a full set of shocks.

¹ The results are reported in the conference volume, *Monetary Policy Rules*, Taylor (1999). Several of the models in this earlier comparison and robustness exercise are also included in our new monetary model database, including Rotemberg-Woodford (1999), McCallum and Nelson (1999), and Taylor (1993).

² See Appendix 1 of this paper for the current list of 35 models and Wieland, Cwik, Müller, Schmidt and Wolters (2009) for a detailed exposition of the platform for model comparison. The model base includes small calibrated text-book-style models, estimated medium- and large-scale models of the U.S. and euro area economies, and some estimated open-economy and multi-country models. Software and models are available for download from <http://www.macromodelbase.com>. This platform relies on the DYNARE software for model solution and may be used with Matlab. For further information on DYNARE see Collard and Juillard (2001) and Juillard (1996) and <http://www.cepremap.cnrs.fr/dynare/>.

First, we examine and compare the monetary transmission process in each model by studying the impact of monetary policy shocks in each model. Second, we calculate and compare the optimal monetary policy rules within a certain simple class for each of the models. Third, we evaluate the robustness of these policy rules by examining their effects in each of the other models relative to the rule that would be optimal for the respective model.

The model comparison and robustness analysis reveals some surprising results. Even though the two more recent models differ from the Taylor (1993a) model in terms of economic structure, estimation method, data sample and data vintage, they imply almost identical estimates of the response of U.S. GDP to an unexpected change in the federal funds rate, that is, to a monetary policy shock. This result is particularly surprising in light of earlier findings by Levin, Wieland and Williams (1999, 2003) indicating that a number of models built after Taylor (1993a) exhibit quite different estimates of the impact of a monetary policy shock and the monetary transmission mechanism.³ We also compare the dynamic responses to other shocks. Interestingly, the impact of the main financial shock, that is the risk premium shock, on U.S. GDP is also quite similar in the Smets and Wouters (2008) and the Taylor (1993) model. This finding is of interest in light of the dramatic increase in risk premia observed since the start of the financial crisis in August 2007.⁴ Differences emerge with regard to the consequences of other demand and supply shocks.

The analysis of optimized simple interest rate rules reveals further interesting similarities and differences across the three models. All three models prefer rules that include the lagged interest rate in addition to inflation deviations from target and output deviations from potential. The two more recent new Keynesian models favour the inclusion of the growth rate of output gaps.

³ For example, the model of Fuhrer and Moore (1995) and the Federal Reserve's FRB/US model of Reifschneider et al (1999), both exhibited longer-lasting effects of policy shocks on U.S. GDP that peak several quarters later than in Taylor (1993a). See Levin, Wieland and Williams (1999, 2003) for a comparison.

⁴ As noted by Smets and Wouters (2007) the risk premium shock represents a wedge between the interest rate controlled by the central bank and the return on assets held by the households and has similar effects as so-called net-worth shocks in models with an explicit financial sector such as Bernanke et al (1999).

The robustness exercise, however, delivers more nuanced results. Model-specific rules with interest rate smoothing and output gaps are not robust. Some degree of robustness can be recovered by focusing on 2-parameter rules with inflation and the output gap, or 3-parameter rules with interest-rate smoothing, inflation and the deviation of output growth from trend instead of output gap growth. This increase in robustness vis-à-vis other models comes at the cost of significant performance deterioration in the original model. Fortunately, however, model comparison offers an avenue for improving over the robustness properties of model-specific rules. Rules that are optimized with respect to the average loss across multiple models achieve very good robustness properties at much lower cost.

2. Brief Description of the Models

Taylor (1993a)

This is an econometrically-estimated rational expectations model fit to data from the G7 economies for the period 1971:1 to 1986:4. All our simulations focus on the United States. The model was built to evaluate monetary policy rules and was used in the original design of the Taylor rule. It has also been part of several model comparison exercises including Bryant et al (1985), Klein (1991), Bryant et al (1993) and Taylor (1999). Shiller (1991) compared this model to the “old Keynesian” models of the pre rational expectations era, and he found that there were large differences in the impact of monetary policy due largely to the assumptions of rational expectations and more structural models of wage and price stickiness.

To model wage and price stickiness Taylor (1993a) used the staggered wage and price setting approach rather than ad hoc lags of prices or wages which characterized the older pre-rational expectations models. However, because the Taylor (1993a) model was empirically estimated it used neither the simple example of constant-length four-quarter contracts presented in Taylor (1980) nor the geometrically-distributed contract weights proposed by Calvo (1983). Rather it lets the weights have a general distribution which is empirically

estimated using aggregate wage data in the different countries. In Japan some synchronization is allowed for.

The financial sector is based on several “no-arbitrage” conditions for the term structure of interest rates and the exchange rate. Expectations of future interest rates affect consumption and investment, and exchange rates affect net exports. Slow adjustment of consumption and investment is explained by adjustment costs such as habit formation or accelerator dynamics. A core principle of this model is that after a monetary shock the economy returns to a growth trend, which is assumed to be exogenous to monetary policy as in the classical dichotomy.

Most of the equations of the model were estimated with Hansen’s instrumental variables estimation method, with the exception of the staggered wage setting equations which were estimated with maximum likelihood.

Christiano, Eichenbaum, Evans (2005)

Many of the equations in the model of Christiano, Eichenbaum and Evans (CEE 2005 in the following) exhibit similarities to the equations in the Taylor model, but they are explicitly-derived log-linear approximations of the first-order conditions of optimizing representative firms and households. Their model also assumes staggered contracts but with Calvo weights and backward-looking indexation in those periods when prices and wages are not set optimally. Long-run growth and short-run fluctuations are modelled jointly rather than separately as in Taylor’s model. Thus, the CEE (2005) model explicitly accounts for labor supply dynamics as well as the interaction of investment demand, capital accumulation and utilization. Furthermore, their model includes a cost-channel of monetary policy. Firms must borrow working capital to finance their wage bill. Thus, monetary policy rates have an immediate impact on firms’ profitability.

The CEE (2005) model was estimated for the U.S. economy over the period 1959:2-2001:4 by matching the impulse response function to the monetary shock in a structural VAR. An important assumption of the VAR that carries over to the model is that monetary policy innovations affect the interest rate in the *same* quarter, but other variables, including output and inflation, only by the *following* quarter.

The monetary policy innovation represents the single, exogenous economic shock in the original CEE model. However, additional shocks can be incorporated in the structural model and the variance of such shocks may be estimated using the same methodology. The additional shocks would first be identified in the structural VAR. Then, the parameters of the structural model including innovation variances would be re-estimated by matching the impulse response functions implied by the model with their empirical counterparts from the VAR. Altig, Christiano, Eichenbaum and Linde (2004), (ACEL 2004 in the following), follow this approach and identify two additional shocks – a neutral and an investment-specific technology shock. These shocks exhibit serial correlation and have permanent effects on the level of productivity. Together with the monetary policy shock they account for about 50% of the variation in output. The impulse response function for the monetary policy shock in ACEL (2004) is almost identical to CEE (2005). Therefore, we will use the ACEL (2004) parameterization of the CEE model for the computational analysis in our paper. A drawback of this model is that it does not yet provide a complete characterization of the observed output and inflation volatility.

The CEE model, which was initially circulated in 2001, represented the first medium-sized, estimated example of the new generation of New-Keynesian dynamic stochastic general equilibrium models explicitly derived from optimizing behavior of representative households and firms.⁵ It stimulated the development of similar optimization-based models for many other countries once Smets and Wouters (2003) showed how to make use of new

⁵ The paper was published in 2001 as NBER Working Paper 8403.



advances in Bayesian techniques (see e.g. Geweke (1999) and Schorfheide (2000)) in estimating such models.

Smets and Wouters (2007)

The model of the U.S. economy estimated by Smets and Wouters (2007) (SW 2007 in the following) with U.S. data from 1966:1 to 2004:4 may be viewed as an extended version of the CEE/ACEL model. The SW model contains a greater set of macroeconomic shocks and aims to fully explain the variation in key variables, such as aggregate output and its components as well as inflation, wages and interest rates. They use a Bayesian estimation methodology that allows the use of priors on model parameters informed from theory and literature. The posterior distributions then incorporate the information in the available macroeconomic data. Whenever the data does not help in pinpointing parameter values very precisely, theoretical priors dominate. Such priors can in some cases be based on evidence from microeconomic studies. The Bayesian estimation methodology has quickly been popularized and widely applied by researchers in central banks and academia. It has been implemented for use with the DYNARE software that we also utilize in our model base.

Smets and Wouters (2007) modify some of the structural assumptions embodied in the CEE/ACEL model. In the long-run, the SW model is consistent with a balanced steady-state growth path driven by deterministic labor-augmenting technological progress. While the CEE model assumes wages and prices are indexed to last period's inflation rate in the absence of a Calvo-style signal, the SW model allows firms to index to a weighted average of lagged and steady-state inflation. Furthermore, SW drop two more assumptions that have important short-run implications in the CEE/ACEL model. First, they do not impose the delayed effect of monetary policy on other variables that CEE built into the structural model so as to match the constraints required by the structural VAR to identify monetary policy shock. Second, SW (2007) do not require firms to borrow working capital to pay the wage bill. Thus, the so-called

cost channel is absent from the model. Smets and Wouters note that they did not find this channel necessary for fitting the dynamics in U.S. data. In our simulations, we will also investigate the implications of adopting the SW assumptions of no cost channel and no timing constraints on monetary policy shocks in the original CEE/ACEL model.

3. Shocks to Monetary Policy as Deviations from Two Policy Rules

We first use the model database to assess the extent of differences between models regarding the transmission of monetary policy to output and inflation. To this end we compare the effect of monetary policy shocks in the three models. A monetary policy shock is defined as a surprise deviation from systematic policy behavior which is characterized by interest rate policy rules.

In our comparison, we focus on two estimated rules used by SW 2007 and CEE 2005 respectively to characterize systematic central bank policy. Smets and Wouters estimate the coefficients of this interest rate rule along with the other equations in their model. We refer to it as the SW rule in the remainder of the paper. They call it a generalized Taylor rule, because it includes the lagged federal funds rate, the lagged output gap, and a serially correlated policy shock, in addition to the current inflation rate and output gap that appear in the original Taylor (1993b) rule. The SW rule implies the following setting for the federal funds rate, i_t :

$$(1) \quad i_t = 0.81i_{t-1} + 0.39\pi_t + 0.97y_t - 0.90y_{t-1} + \varepsilon_t^i, \quad \text{where} \quad \varepsilon_t^i = 0.15\varepsilon_{t-1}^i + \eta_t^i$$

Here, π_t refers to the annualized, quarterly inflation rate and y_t to the output gap.⁶ In the SW and CEE model the gap measure used in the policy rule is defined as the difference between the actual output level and the level that would be realized if prices adjust flexibly to macroeconomic shocks, the so-called flex-price output level.⁷ In the Taylor model (and the original Taylor rule) the output gap is defined as difference between actual output and long-run potential output as measured by the trend. The policy shock is denoted by ε_t^i and follows a first-order autoregressive process with an IID normal error term, η_t^i . As a result of serial correlation and the inclusion of the lagged interest rate in the reaction function, an IID innovation will have a persistent effect on nominal interest rates and due to price rigidity also on real rates and aggregate output.

CEE (2005) define the central bank's policy rule in terms of a reaction function for the growth rate of money.⁸ They identify monetary policy shocks in a structural VAR as orthogonal innovations to the interest rate reaction function. Then, they estimate the parameters of the structural model including the parameters of the money growth rule by matching the impulse response in the structural model and the VAR. In addition, they contrast their findings under the money growth rule with the effect of a policy shock under an extended Taylor rule for the federal funds rate:⁹

$$(2) \quad i_t = 0.80i_{t-1} + 0.3E_t\pi_{t+1} + 0.08y_t + \varepsilon_t^i$$

Just like the SW rule it incorporates partial adjustment to the lagged federal funds rate. However, it is forward-looking and responds to the expected inflation rate for the upcoming

⁶ Note, the response coefficients differ from the values reported in SW 2007. In equation (1), interest and inflation rates are annualized, while SW used quarterly rates. The original specification in SW 2007 corresponds to $i_t^q = (1-0.81)(2.04\pi_t^q + 0.09y_t) + 0.22\Delta y_t + 0.81i_{t-1}^q + \varepsilon_t^i$, where the superscript q refers to quarterly rates.

⁷ Smets and Wouters set wage and price markup shocks equal to zero in the derivation of the flex-price output measure used to define their output gap.

⁸ CEE (2005) and ACEL(2004) model monetary policy in terms of innovations to the growth-rate of money that they denote by μ_t : $\mu_t = \mu + \theta_0\varepsilon_t + \theta_1\varepsilon_{t-1} + \theta_2\varepsilon_{t-2} + \theta_3\varepsilon_{t-3}\dots$

⁹ Note, we use annualized interest and inflation rates and transcribe the CEE rule accordingly. In CEE 2005 they define their rule as: $i_t^q = (1-0.80)(1.5E_t\pi_{t+1}^q + 0.1y_t) + 0.8i_{t-1}^q + \varepsilon_t^i$. CEE (2005) attribute this estimated rule to Clarida et al (1999). However, the coefficients reported in Clarida et al (1999) are different. Their rule corresponds to $i_t = (1-0.79)(2.15E_t\pi_{t+1} + 0.93y_t) + 0.79i_{t-1} + \varepsilon_t^i$.

quarter. The coefficient on the output gap is much smaller than in the SW rule and it does not include the lag of the output gap. The policy shock is IID. In the following we refer to this rule as the CEE rule.

4. Monetary Policy Shocks in Three Monetary Models of the U.S. Economy

We compare the consequences of a monetary policy shock in the Taylor, SW and CEE/ACEL models to shed light on their implications for the transmission of Federal Reserve interest rate decisions to aggregate output and inflation. In particular, we want to find out to what extent the current-generation DSGE models, CEE/ACEL (2004) and SW (2007), imply quantitatively different effects of monetary policy than the model by Taylor (1993a). Since the models differ in terms of economic structure and parameter estimates are obtained for different data series, estimation periods and data vintages, we would expect to obtain quantitatively different assessments of the monetary transmission mechanism.

Figure 1 reports the consequences of a 1 percentage point shock to the federal funds rate for nominal interest rates, output and inflation. The panels on the left-hand side refer to the outcomes when the Federal Reserve sets interest rates following the initial shock according to the prescriptions of the SW rule, while the right-hand-side panels refer to the outcome under the CEE rule. Each panel shows the findings from four model simulations. The dark solid line refers to the SW model, the light solid line to the TAYLOR model, the dashed line to the CEE/ACEL model and the dotted line to the CEE/ACEL model with SW assumptions.¹⁰

Surprisingly, the effect of the policy shock on real output and inflation given a common policy rule is very similar in the four models. For example, under the SW rule the nominal interest rate increases on impact by 0.8 to 1 percentage points and then returns slowly to

¹⁰ The CEE/ACEL model with SW Assumptions implies the following modifications: We remove the timing constraints that were imposed on the structural model by the authors so that it coincides with the identification restrictions on the VAR that they used to obtain impulse responses for the monetary policy shock. Furthermore we remove the constraint from the ACEL model that requires firms to finance the wage bill by borrowing cash in advance from a financial intermediary. As a result of this constraint the interest rate has a direct effect on firms' costs.

steady state, real output falls over three to four quarters to a trough of about -0.35 percent before returning to steady-state, and inflation declines more slowly with a trough of about 20 basis points roughly 2 to 3 quarters later than output.

The quantitative implications for real output in the Taylor (1993) and SW (2007) models are almost identical. The outcome under the CEE/ACEL model initially differs slightly from the other two models. In the quarter of the shock we observe a tiny increase in output, while inflation does not react at all. From the second quarter onwards output declines to the same extent as in the other two models but the profile is shifted roughly one quarter into the future. The decline in inflation is similarly delayed. Once we implement the CEE/ACEL model with the SW assumptions of no timing constraint on policy and no cost channel, the timing of output and inflation dynamics is more similar to the other two models.

The outcome of a monetary policy shock given the Fed follows the CEE rule is shown in the right-hand-side panels of **Figure 1**. Again, the magnitude of the effect of the policy shock on real output and inflation is almost identical in the Taylor model, the SW model and the ACEL/CEE model, particularly when the latter model is implemented with the SW assumptions. Furthermore, the reduction in output is very similar to the case when the Fed follows the SW rule. The decline in inflation is a bit smaller.

The original Lucas critique stated that a change in the systematic component of policy can have important implications for the dynamics of macroeconomic variables. Thus, it is not surprising that the output and inflation effects of monetary policy shocks change if we consider a wider set of monetary policy rules. For example, in the case of the original Taylor (1993b) rule an IID policy shock would influence the nominal interest rate only for one period, because the Taylor rule does not include the lagged interest rate. We have investigated the real output effects of a monetary policy shock with different response coefficients (for example, a four times smaller response to output), different inflation measures (such as year-on-year inflation) and different rules such as the original Taylor rule or the benchmark rules

considered in Levin, Wieland and Williams (2003) and Kuester and Wieland (2010). Different rules have quite different implications for the real consequences of monetary policy shocks. However, the Taylor model, the SW model and the CEE model continue to imply surprisingly similar dynamics of aggregate real output and inflation in response to a policy shock for a given, common policy rule.

The finding that the two best-known models of the recent generation of new Keynesian models provide very similar estimates of the impact of a policy shock on U.S. real GDP as the model of Taylor (1993a) is particularly surprising in light of earlier comparison projects. For example, the comparison in Levin, Wieland and Williams (1999) and (2003) indicated that models built and estimated after Taylor (1993a) such as the model of Fuhrer and Moore (1995) or the Federal Reserve's FRB/US model of Reifschneider, Tetlow and Williams (1999) provided different assessments of the U.S. monetary transmission mechanism. In particular, these models suggested that the impact of monetary policy shocks on real output would be longer-lasting and reach its peak more than a year after the initial impulse. This view is often considered conventional wisdom among practitioners. The model data base associated with this paper also allows users to replicate the impulse response function comparison in the Fuhrer and Moore and FRB/US models.

So far we have focused on the overall effect of the policy shock on output and inflation. Now we turn to the effects on other macroeconomic variables. **Figure 2** illustrates some additional common aspects of the transmission mechanism in the three models of the U.S. economy, while **Figure 3** highlights interesting differences. Monetary policy is assumed to follow the SW rule after the policy shock.¹¹ The real interest rate increases almost to the same extent in all three models as shown in panel 2a. As a result, aggregate consumption and aggregate investment decline. The decline in consumption is smaller in the Taylor model than in the other two models, while the decline in investment is much greater. The quantitative

¹¹ Similar figures for the case of the CEE rule are provided in Appendix 2.

comparison of the dynamics of GDP components, however, is hampered by the fact that the models use different deflators in generating real consumption and investment series.¹² Another similarity regarding monetary policy transmission in the three models is that real wages decline along with aggregate demand following the monetary policy shock.

The three models also exhibit some interesting differences regarding monetary policy transmission. For example, panels a. and b. in **Figure 3** indicate that only the Taylor model accounts for international feedback effects. As a result of the policy shock the US dollar appreciates temporarily in real trade-weighted terms. Exports and imports, both, decline. However, the fall in imports is much greater than in exports and as a result net exports increase. The strong decline in imports occurs due to the domestic demand effect that figures very importantly in the U.S. import demand equation. The resulting increase in net exports partly offsets the impact of the large negative decline in investment demand on aggregate output in the Taylor model. Furthermore, panels c. through f. in **Figure 3** illustrate that only the SW and CEE models account for the effects of the policy shock on labor supply, capital stock, the rental rate of capital and capital utilization. All four measures decline in response to the monetary shock. This explanation of supply-side dynamics is missing from the Taylor model.

5. Other shocks and their implications for policy design

Unexpected changes in monetary policy are of interest in order to identify aspects of the monetary transmission mechanism. When it comes to the question of policy design, however, the standard recommendation is to avoid policy surprises since they only generate additional

¹² While the Taylor model simulates the components of GDP in real terms, the simulations in the SW and CEE models concern the nominal components divided by the GDP deflator. It is not possible to make the series directly comparable because none of the models accounts for the consumption and investment deflators separately from the GDP deflator.

output and inflation volatility. Instead optimal and robust policy design focuses on the proper choice of the variables and the magnitude of the response coefficients in the policy rule that characterizes the systematic component of monetary policy. The policy rule is then designed to stabilize output and inflation in the event of shocks emanating from other sectors of the economy. In this respect, it is of interest to review and compare the potential sources of economic shocks in the three models under consideration.

In light of the recent financial crisis, we start by comparing the effect of particular financial shocks. Only the Taylor and SW models contain such shocks. **Figure 4** illustrates the effect of an increase in the term premium by 1 percentage point on real output and inflation in the Taylor and SW models. The initial impact of these shocks on real output is almost identical in the two models and lies between -0.22 and -0.24 percent of output. This finding is particularly surprising since the shocks are estimated quite differently in the two models. In the Taylor model the term premium shock is estimated from the term structure equation directly using data on short- and long-term interest rates, that is, the federal funds rate versus 10-year US treasuries. In the SW model the risk premium shock is estimated from the consumption and investment equation. It assumes the term structure relation implicitly but uses no data on long-term rates. In earlier work on the euro area, Smets and Wouters (2003) included instead a consumption demand or preference shock. This shock is omitted in their model of the U.S. economy to keep the number of shocks in line with the number of observed variables. SW emphasize that the premium shock represents a wedge between the interest rate controlled by the central bank and the return on assets held by the households and has similar effects as so-called net-worth shocks in models with an explicit financial sector such as Bernanke et al (1999).¹³

¹³ In the model file available from the AER website along with the SW (2007) paper the shock is multiplied with minus the consumption elasticity. This is consistent with figure 2 of that paper, where the shock appears as a “demand” shock, i.e. an increase has a positive effect on output. It is not consistent with equation (2) in SW (2007) that identifies the shock as a risk premium shock (i.e. an increase has a negative effect). We have modified the model file consistent with the notation as risk premium shock in equation (2) in SW (2007). In

Figure 5 provides a comparison of what could be termed “demand” or “spending” shocks in the three models. These are shocks that push output and inflation in the same direction. The Taylor model contains many such shocks. Panels a. and b. show the effects of shocks to non-durables consumption, equipment investment, inventory investment, government spending and import demand on the output gap and inflation. The SW model contains two shocks of this type, an exogenous spending shock that comprises government spending as well as net exports and an investment-specific technology shock. The ACEL model contains an investment-specific technology shock that initially lowers inflation but then raises it. It has stronger long-term effects than the investment-specific technology shock in SW (2007).

Figure 6 compares supply shocks in the three models, i.e. shocks that push output and inflation in opposite directions. The Taylor model has a number of such shocks, in particular innovations to the contract wage equations, the final goods price equation, import prices and export prices. The SW model contains price mark-up and wage mark-up shocks that are somewhat similar to the contract wage and aggregate price shocks in the Taylor model. Only the SW and the ACEL models include neutral technology shocks. In the ACEL model these shocks have a long-term effect on productivity growth, while their effect on productivity growth in the SW model is temporary.

Comparing the three models, it is important to keep in mind that only the Taylor and SW model aim to fully explain the variation in the macroeconomic variables included in the model as an outcome of exogenous shocks and endogenous propagation. The ACEL model only aims to explain that part of the variation that is caused by the three shocks in the structural VAR that was used to identify them. **Figures 5** and **6** indicate that the investment-specific and neutral technology shocks in the ACEL model have negligible effects on inflation. Consequently, the ACEL model omits most sources of inflation volatility outside of policy shocks and is of limited usefulness for designing monetary policy rules. With this

addition, we have checked that re-estimating the SW model with the shock entering the consumption Euler equation as defined by equation (2) in their paper does not have an important effect on the parameter estimates.

caution in mind, we will nevertheless explore the implications of the ACEL model for policy design together with the other two models.

6. Optimal simple policy rules in the Taylor, CEE/ACEL and SW models

The first question on policy design, that we address concerns the models' recommendations for the optimal policy response to a small number of variables in a simple interest rate rule. We start by considering rules that incorporate a policy response to two variables, that is, the current year-on-year inflation rate and the output gap as in the original Taylor (1993b) rule:

$$(3) \quad i_t = \alpha\pi_t + \beta_0 y_t$$

In the SW and ACEL models, the output gap y is defined as the deviation of actual output from the level of output that would be realized if the price level were fully flexible. This flexible-price output varies in response to some of the economic shocks. We use the same definition of flexible price output as in Smets and Wouters (2007). In the Taylor model the gap is calculated relative to a measure of potential that grows at an exogenous rate.

In a second step, we extend the rule to include the lagged nominal interest rate as in Levin, Wieland and Williams (1999, 2003):

$$(4) \quad i_t = \rho i_{t-1} + \alpha\pi_t + \beta_0 y_t$$

Then, we also include the lagged output gap as in the estimated rule in the Smets and Wouters (2007) model:

$$(5) \quad i_t = \rho i_{t-1} + \alpha\pi_t + \beta_0 y_t + \beta_1 y_{t-1}$$

We choose the response coefficients of the rules (i.e. ρ , α , β_0 , β_1) in each of the models by minimizing a loss function L that includes the unconditional variances of inflation, the output gap and the change of the nominal interest rate:

$$(6) \quad L = \text{Var}(\pi) + \lambda_y \text{Var}(y) + \lambda_{\Delta i} \text{Var}(\Delta i)$$

This form of loss function has been used extensively in earlier analyses, including the above-mentioned model comparison studies. With $\lambda_{\Delta i}=0$, it corresponds to the unconditional expectation of a second-order approximation of household utility in a small New-Keynesian model derived from microeconomic foundations as shown in Rotemberg and Woodford (1999). The magnitude of the implied value of λ_y is very sensitive to the particular specification of overlapping nominal contracts: random-duration “Calvo-style” contracts imply a very low value on the order of 0.01, whereas fixed-duration “Taylor-style” contracts imply a value near unity (Erceg and Levin (2001)). For this reason, we consider values of $\lambda_y=(0, 0.5,1)$. In addition, we assign a positive weight to interest volatility and consider values of $\lambda_{\Delta i}=(0.5,1)$. It is intended to capture central banks’ well-known tendency to smooth interest rates and to avoid extreme values of optimized response coefficients that would be very far from empirical observation and regularly violate the non-negativity constraint on nominal interest rates (Woodford 1999).

The optimized response coefficients are shown in **Table 1**. It reports results for two-, three- and four-parameter rules in the Taylor, SW and CEE/ACEL models. The central bank’s objective is assumed to assign a weight of unity to inflation and interest rate volatility

and either a weight of zero or unity to output gap volatility.¹⁴ First, with regard to two-parameter rules all three models prescribe a large response coefficient on inflation and a small coefficient on the output gap, if the output gap does not appear in the loss function. If the output gap receives equal weight in the loss function then the optimal coefficient on output increases but remains quite a bit below the response to inflation. The coefficient on inflation declines in the SW and CEE/ACEL models but increases in the Taylor model when output appears in the loss function.

For three-parameter rules the optimized value of the coefficient on the lagged nominal interest rate is near unity. This property applies in all three models and with different values of the objective function weights except for one case that is discussed below. The coefficients on inflation are much smaller than in the two-parameter rules but they typically remain positive.

In the ACEL model the loss function is very flat. There appear to be multiple local optima and the global optimum we identify has very extreme coefficients in the case of the three-parameter rule with a positive weight on output gap volatility in the loss function.¹⁵ As noted earlier, a weakness of the ACEL model is that it only contains two technology shocks that explain little of the variation of inflation and output gaps but have permanent effects on the growth of steady state output. The ACEL model contains no short-run demand and supply shocks as do the other two models. For this reason the model may not be considered suitable in its current form for an evaluation of the role of interest rate rules in stabilization policy.

¹⁴ Additional findings for a weight of 0.5 on the unconditional variance of the change of the nominal interest rate are reported in Appendix 2. Further sensitivity studies for intermediate weights have been conducted and are available from the authors upon request.

¹⁵ A local optimum at less extreme values is observed for $\rho = 0.01$, $\alpha = 2.9$, $\beta_0 = 0.5$.

Nevertheless, we continue to replicate the analysis conducted in the other two models also in the ACEL model throughout this paper.¹⁶

Next, we turn to the rules with four parameters that include the lagged output gap in addition to current output, inflation and the lagged interest rate. The coefficients on the lagged interest rate typically remain near unity. Interestingly, the coefficient on the lagged output gap, that is β_1 , in the CEE/ACEL and SW models is almost equal to $-\beta_0$, the coefficient on the current output gap. Thus, the CEE/ACEL and SW models appear to desire a policy response to the growth rate of the output gap rather than its level. In fact, restricting $\beta_1 = -\beta_0$ and re-optimizing the response coefficients in these models implies a coefficient of 1.65 in the SW and 2.0 in the ACEL model, respectively. Changes in the other response coefficients are very limited. By contrast, in the Taylor model, which uses trend output as a measure of potential, the optimal coefficients on current and lagged output gaps are both positive.

Different findings between the Taylor model and the SW and CEE/ACEL models may be due to different definitions of potential output. The flex-price output level used as a measure of potential in the SW and CEE/ACEL models exhibits substantial variation due to economic shocks and its growth rate may deviate substantially from trend growth.¹⁷ Thus, simply differencing the output gap in our policy rule does not eliminate the effect of different concepts of potential output on the optimized response coefficients. Instead, we proceed to evaluate the performance of a fourth class of rules that respond to the deviation of actual GDP growth from trend (or steady-state) growth, denoted by Δy_t :

$$(7) \quad i_t = \rho i_{t-1} + \alpha \pi_t + \beta_{\Delta} \Delta y_t$$

¹⁶ Following the suggestion of an anonymous referee, we have investigated whether the SW model exhibits similar properties as the ACEL model if the number of shocks is reduced to the investment-specific and the neutral technology-shock as in ACEL. We find that the response coefficients on inflation and the output gap in the two-parameter and three-parameter rules increase in absolute terms. However, the three parameter rule in the SW model does not take the extreme coefficient values observed in the ACEL model, nor do we observe multiple local optima as in the ACEL model. We make these findings available along with other material in Appendix 2.

¹⁷ A number of recent contributions have emphasized the differences between flex-price measures of potential and more traditional views on the trending components of real activity (see Palmqvist (2007), Basu and Fernald (2009) and Gupta (2009)).

In this manner, potential output growth is defined similarly across the three models. Researchers such as Orphanides (2003) have recommended such rules as a way to reduce the impact of central bank misperceptions about the level of potential output on interest rate setting.¹⁸ The last 3 rows in **Table 1** report the optimal coefficients of the 3-parameter policy rule with deviations of actual from steady-state output growth.

If output gap variability does not appear in the loss function, ($\lambda_y=0$), the optimal coefficient on output growth, $\beta_{\Delta y}$, is very close to zero, just as in the 3-parameter rules with the output gap. If output variability receives a weight of unity in the loss function, the optimal interest rate rule responds positively to output growth, at least in the Taylor and SW models. In the ACEL models it is near zero. Thus, in the SW and ACEL models, it matters quite a lot whether the rule uses the deviation of actual GDP growth from trend growth or from flexible-price output growth.

Table 2 reports on the relative stabilization performance with two-, three- and four-parameter rules. Two different measures are reported, the percentage increase in loss and, in parentheses, the absolute increase in loss when one reduces the number of parameters (and therefore variables) in the policy rule starting from the case of four-parameter rules. In the following, we will focus on the absolute loss differences because the percentage differences tend to give misleading signals.

The particular measure of the increase in absolute loss that is shown is the implied inflation variability premium proposed by Kuester and Wieland (2010) (referred to as the IIP in the following). This measure translates a particular increase in absolute loss into the increase in the standard deviation of inflation (in percentage point terms) that would raise the loss to the same extent keeping all else equal (i.e. for a constant output or interest volatility). The advantage of this measure is that it is easily interpreted in practical terms and therefore

¹⁸ See also Schmitt-Grohe and Uribe (2004) and Burriel, Fernández-Villaverde and Rubio-Ramírez (2009). Beck and Wieland (2008) have instead proposed a non-linear cross-checking mechanism that would correct the prescriptions from an output gap-based rule whenever there is statistical evidence of distorted policy outcomes, but take advantage of gap estimates in normal times.

provides a clear signal of those properties of interest rate rules that are of economic importance.

To give an example, consider the number in the fourth row and third column of **Table 2** in parentheses. Its value is 2.14 and it implies the following: if the Taylor model represents the U.S. economy and the central bank considers using the optimized two-parameter rule instead of an optimized three-parameter rule, and if the central bank's loss-function assigns equal weight to output and inflation, the resulting increase in loss (due to higher inflation, output and interest volatility) is equivalent to an increase in the standard deviation of inflation of 2.14 percentage points all else equal. This difference is economically important. Although, it is the largest IIP reported in the table the associated percentage increase of 98.8% is only the fourth-largest in the table. The third-largest percentage increase in the table is 229%. It is associated with a switch from the three-parameter to the two-parameter rule in the ACEL model when the central bank's loss function assigns zero weight to output volatility. However, the associated IIP of 0.04 is tiny. Thus, the particular switch in rule is economically irrelevant in spite of the large percentage increase in loss. In this case, the reason is that the ACEL model only contains two shocks that cause little inflation volatility and very small losses.

The findings in **Table 2** suggest that there is little additional benefit from including the lagged output gap in the rule. Dropping the lagged output gap from the rule barely increases the central bank's loss. The associated IIP's in the first column of Table 2 lie between 0.001 and 0.47. However, it appears very beneficial to include the lagged interest rate in the rule. Dropping the lagged interest rate from the rule and moving from three to two response parameters implies an economically significant increase in the central bank's loss function, in particular in the SW and Taylor models, where it is equivalent to an increase in the standard deviation of inflation by 1 and 2 percentage points, respectively, (3rd column in Table 2). Among three-parameter rules, the rule with the output gap performs better than the rule with

growth rate of output (in deviation from trend growth) across all three models. As shown in the middle column of Table 2 the IIP's relative to the four-parameter rule are uniformly greater for the growth rate than the gap version. They are particularly large in the Taylor model. However, the growth-rate version of the three-parameter rule still performs better than the 2-parameter rule with inflation and the output gap.

7. Robustness

What if the model used by the central bank in designing a policy rule is not a good representation of the economy and one of the other two models provides a much better representation of the U.S. economy? In other words, how robust are model-specific optimized policy rules with respect to the range of model uncertainty reflected in the three models considered in this paper? **Table 3** provides answers to these questions. Robustness is measured in the following manner. The rule optimized for model X is implemented in model Y. The resulting loss in model Y is compared to the loss that would be realized under the rule with the same number of parameters that has been optimized for that particular model. The difference is expressed in terms of IIP only.

The findings in **Table 3** show that from the perspective of a central bank that aims to minimize inflation and interest rate volatility but assigns no weight to output volatility ($\lambda_y=0$), all four classes of policy rules are quite robust. Typically, a rule optimized in one of the models performs quite well in any of the other model compared to the best possible rule with the same number of parameters in that model.

Unfortunately, the preceding conclusion is almost completely reversed when one takes the perspective of a policy maker who cares equally about output and inflation volatility, that is when $\lambda_y=1$. In this case, only the 2-parameter rules remain fairly robust. The lack of robustness is most pronounced for 3- and 4-parameter rules that use output gaps. While these

rules offer substantial performance improvements when the true model is known, performance can deteriorate markedly if the economy is better approximated by another model. For example, using the 4-parameter rule that is optimal in the SW model instead in the Taylor model, implies an IIP of 2.71. Alternatively, the 4-parameter rule optimized for the Taylor model implies an IIP of 7.18 in the SW model and generates multiple equilibria in the ACEL model.

Similar problems arise with regard to 3-parameter rules that use the output gap, even if the CEE/ACEL model is excluded from the robustness analysis because of its odd behaviour under such rules as discussed earlier. As shown in the second column of **Table 3**, the rule optimized in the Taylor model implies an IIP of 5.41 in the SW model, while the rule optimized for the SW model delivers an IIP of 3.20 in the Taylor model. Replacing the output gap in the 3-parameter rules with the deviation of output growth from its trend improves their robustness properties at the cost of substantial performance deterioration in the true model as shown previously in **Table 2**. However, the IIP's are not negligible and remain near or above unity in three cases, two of which concern the rule optimized in the ACEL model.

Only the rules with two parameters that respond to inflation and the current output gap deliver a fairly robust stabilization performance across the three models. The IIP's are always substantially below unity and often near zero. Thus, a policymaker with a strong preference for robustness against model uncertainty might prefer to choose an optimized two-parameter rule that responds to inflation and the output gap but not the lagged interest rate.

Unfortunately, such rules perform quite a bit worse than rules with interest-rate smoothing when it is known which of the models best captures the true dynamics in the economy. To quantify this loss, we re-evaluate robustness with respect to the best 4-parameter rule when the model is known, rather than the best rule of the same class. With respect to this benchmark 2-parameter rules exhibit IIP's of 2.64 (SW rule in Taylor model) and 1.53 (Taylor rule in SW model), respectively. Thus, they remain more robust than 3- and 4-

parameter rules with output gaps. However, 3-parameter rules that replace the output gap with the deviation of actual GDP growth from trend perform slightly better from this perspective as long as the ACEL model is excluded from the comparison. They exhibit IIP's of 2.28 (SW rule in Taylor model) and 1.21 (Taylor rule in SW model), respectively, when compared to the 4-parameter rule optimized for the correct model.

Using the model database, however, it is possible to produce policy recommendations that are more robust than those based on a single model. For example, one may optimize a particular policy rule with respect to multiple models by minimizing the average loss across models. This approach has been proposed by Levin, Wieland and Williams (2003) and Brock, Durlauf and West (2003), among others. In this case, the response coefficients of the rules, $(\rho, \alpha, \beta_0, \beta_1, \beta_\Delta)$, are chosen to minimize the average loss across the three models:

$$(8) \quad \sum_{m \in M} \frac{1}{3} L_m = \sum_{m \in M} \frac{1}{3} (Var(\pi_m) + \lambda_y Var(y_m) + \lambda_{\Delta i} Var(\Delta i_m))$$

Here, the subscript m refers to a particular element of $M=(TAYLOR, SW, ACEL)$ – the set of available models. We focus on the performance of such rules in those cases where model-specific rules were not robust, that is when the central bank assigns similar weights to output and inflation in the loss function. The parameter values for the model averaging rules are reported in **Table 4**. The 2-parameter rules remain fairly similar to the model-specific optimization because those were already quite robust. The interest-smoothing coefficient for 3- and 4-parameter rules now lies very close to unity, in between the values that are optimal in the SW and the TAYLOR model. The response to inflation is small but positive ranging from 0.2 to 0.4 depending on whether the rules include current and lagged output gaps or the deviation of output growth from trend. Response coefficients on the current output gap, output gap growth or output growth deviations from trend vary between 0.2 and 0.8.

As shown in **Table 5**, model averaging generally improves the robustness of all four classes of simple policy rules that we have evaluated. Again, the numerical values reported in

different cells of the table refer to the increase in the loss function – expressed in terms of inflation variability premia (IIP) – when a rule optimized in model X is used in model Y and evaluated relative to the same type of rule optimized in model Y. By this measure 2-parameter rules that respond to inflation and the output gap are the rules that are most robust to model uncertainty. The robustness properties of rules with interest rate smoothing that respond to inflation and output growth deviations from trend are slightly worse. However, this ordering can be reversed if the 4-parameter rule optimized in the correct model is used as benchmark (IIP values in parentheses) and the ACEL model is dropped from the comparison. More importantly, model averaging helps to identify rules with interest rate smoothing and a response to output gaps that are fairly robust to model uncertainty, while regaining much of the improvement in stabilization performance promised by such rules in the absence of model uncertainty.

We note that model averaging mirrors Bayesian decision-making with equal prior beliefs. Kuester and Wieland (2010) compare Bayesian decision-making with worst-case analysis and ambiguity aversion, which combines both objectives, in an application that deals with monetary policy modelling in the euro area. They also explore the impact of learning on posteriors and Bayesian objectives over time.

8. Conclusions and Extensions

The preceding comparison of the Taylor (1993a) model with the two well-known examples from the current generation of new Keynesian models of the U.S. economy by Christiano, Eichenbaum and Evans (2005) and Smets and Wouters (2007) indicates a surprising similarity of the monetary transmission mechanism. The empirical, model-based assessment of the impact of an unanticipated change in the federal funds rate on real U.S. GDP has not changed in 14 years that lie in between the publication of these models. This finding is encouraging for

policy makers that want to rely on such models. It differs from earlier comparison projects which showed that models built later in the 1990s such as the FRB/US model suggested that the impact of policy shocks on real output was much more drawn out over time. Conventional wisdom on the lags of monetary policy decisions may therefore need to be revised.

The robustness analysis of simple policy rules with the three models reveals less similarity than the comparative assessment of the transmission mechanism. If the central bank has the task of stabilizing both output and inflation, then an optimal rule derived in one of our models is not robust in the other models. By sacrificing optimality in each model one can identify some policy rules that are fairly robust, in particular, 2-parameter rules that respond to inflation and the output gap and 3-parameter rules that include interest rate smoothing but replace the output gap with the deviation of GDP growth from trend.

We also find that model averaging substantially improves the robustness properties of policy rules. Hence, using a model database, such as the one described in this paper, one can derive policy rules that are more robust to model uncertainty than those obtained with a single preferred model.

Our findings also suggest at least two important extensions focusing on (1) the implications of utility-based loss functions and (2) a wider range of macroeconomic models.

Utility Based Loss Functions

We selected the loss function in equation (6) because it has been used extensively in the past and because it corresponds to the unconditional expectation of a second-order approximation of household utility in a small New-Keynesian model derived from microeconomic foundations. However, if the loss function is interpreted as a measure of utility, then its parameters ($\lambda_y, \lambda_{\Delta i}$) are model-dependent (as we noted previously) and the list of variables appearing in the loss function must be expanded. For example, if wage rigidities are present in addition to price rigidities, not only price but also wage fluctuations will affect household

utility. Onatski and Williams (2004) derive the following quadratic approximation of the unconditional expectation of household utility in the model of Smets and Wouters (2003):

$$(9) \quad L_{OW2004} = E[\pi_t^2 + 0.21K_{t-1}^2 - 0.51\pi_t\pi_{t-1} + 0.24(w_t + \pi_t)(w_t - w_{t-1})]$$

Here w_t refers to the real wage and K_{t-1} to the lagged capital stock. To illustrate how such a loss function would affect our results, we optimized the four types of simple policy rules with respect to this utility-based loss in the SW model augmented with the variance of the change of the interest rate, and summarize them here. Interestingly, the optimized 2-, 3- and 4-parameter rules have fairly similar welfare implications under the Onatski-Williams approximation of household utility in the Smets-Wouters model with a maximum difference of 1.17 in IIP terms. We also evaluate the robustness of rules optimized with respect to the simpler loss function defined by equation (6) under this new loss function. Again, model-specific 2-parameter rules with inflation and the output gap, and 3-parameter rules with interest-rate smoothing, inflation and output growth deviations from trend remain fairly robust, but not the other model-specific rules. More details about these results are available in Appendix 2.

Robustness to other macroeconomic models

While we have focused on three models of the U.S. economy, the new monetary model database offers the possibility of comparing many other empirically estimated models. With regard to future research, it would be of great interest to investigate the robustness of monetary policy rules in models that offer a more detailed treatment of the financial sector. As an illustration we extended our model comparison and robustness analysis to include the model of De Graeve (2008). De Graeve introduces a financial intermediary, capital goods producers and entrepreneurs as in Bernanke et al (1999) in a medium-size DSGE model of the same type as the CEE and SW models we have considered. His model, which he estimates with Bayesian methods, generates an endogenous external finance premium that is impacted

by a variety of economic shocks. Interestingly, we find that the GDP response to a monetary policy shock in the De Graeve (DG) model remains very close to the impulse responses in the Taylor, SW and CEE/ACEL models reported in **Figure 1**. The robustness of optimized model-specific rules, however, deteriorates further once we include the DG model. Especially 2-parameter rules optimized in the DG model perform badly in the Taylor and SW models. However, model-averaging rules remain very robust. In fact, they need not be changed. Including the DG model in the model-averaging loss function defined by equation (8) has only a marginal effect on the optimal response coefficients in the policy rules. More information about these results is available in Appendix 2.

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Table 1
Optimal Simple Policy Rules¹⁾

Rules: $i_t = \rho i_{t-1} + \alpha \pi_t + \beta_0 y_t + \beta_1 y_{t-1} + \beta_\Delta \Delta y_t$

Rule /Model	Loss ($\lambda_y = 0$): $Var(\pi) + Var(\Delta i)$					Loss ($\lambda_y = 1$): $Var(\pi) + Var(y) + Var(\Delta i)$				
	ρ	A	β_0	β_1	β_Δ	ρ	α	β_0	β_1	β_Δ
	2 Parameters (Gap) ²⁾					$\alpha \pi_t + \beta_0 y_t$				
TAYLOR		2.54	0.19				3.00	0.52		
SW		2.33	-0.10				2.04	0.26		
CEE/ACEL		4.45	0.28				2.57	0.45		
	3 Parameters (Gap)					$\rho i_{t-1} + \alpha \pi_t + \beta_0 y_t$				
TAYLOR	0.98	0.37	0.09			0.98	0.21	0.53		
SW	1.06	0.49	0.01			1.13	0.012	0.015		
CEE/ACEL	0.97	0.99	0.02			2.84	7.85	-2.12		
	4 Parameters (Gaps)					$\rho i_{t-1} + \alpha \pi_t + \beta_0 y_t + \beta_1 y_{t-1}$				
TAYLOR	0.98	0.37	0.07	0.02		0.96	0.18	0.41	0.19	
SW	1.06	0.46	-0.03	0.03		1.07	0.16	1.63	-1.62	
CEE/ACEL	1.01	1.11	0.18	-0.18		1.04	0.51	2.24	-2.30	
	3 Parameters (Growth) ³⁾					$\rho i_{t-1} + \alpha \pi_t + \beta_\Delta \Delta y_t$				
TAYLOR	1.01	0.52			0.07	1.13	0.40			0.68
SW	1.03	0.48			-0.01	1.01	0.20			1.04
CEE/ACEL	1.02	1.07			-0.02	0	3.71			.002

Notes:

¹⁾ The loss function includes the variance of inflation and the variance of the first-difference of nominal interest rates with a weight of unity, $\lambda_{\Delta i}=1$. λ_y denotes the weight on the variance of the output gap.

²⁾ In the Taylor model the output gap denotes the difference between actual and trend output. In the SW and ACEL models it is the difference to the level realized under flexible prices given current macroeconomic shocks.

³⁾ The output growth measure Δy_t is defined relative to steady-state/trend output growth in all three models.

Table 2
Increase in Loss when Reducing the Number of Parameters in the Rule
 Percentage Increase (Increase in IIP)¹⁾

Models	Loss ($\lambda_y = 0$): $Var(\pi) + Var(\Delta i)$		
	4 versus 3 Parameters (Gaps)	4 Parameters (Gaps) vs 3 Par. (Growth)	3 versus 2 Parameters (Gaps)
TAYLOR	0.12% (0.001)	13.5% (0.10)	278% (1.38)
SW	0.22% (0.001)	1.40% (0.01)	316% (0.78)
CEE/ACEL	5.10% (0.001)	10.0% (0.003)	229% (0.04)
	Loss ($\lambda_y = 1$): $Var(\pi) + Var(y) + Var(\Delta i)$		
TAYLOR	1.81% (0.07)	67.1% (1.61)	98.8% (2.14)
SW	10.6% (0.47)	18.1% (0.76)	25.6% (1.17)
CEE/ACEL	14.4% (0.11)	36.7% (0.22)	9.67% (0.11)

Notes:

¹⁾The values in parentheses measure the increase in absolute loss in terms of the implied inflation (variability) premia proposed by Kuester and Wieland (2010). The IIP corresponds to the increase in the standard deviation of the inflation rate (in percentage point terms) that would imply an equivalent increase in absolute loss.

Table 3
Robustness of Policy Rules

Increase in IIP¹⁾ when a rule optimized in model X is used in model Y
and evaluated relative to the same type of rule optimized in model Y

Loss ($\lambda_y=0$): $Var(\pi) + Var(\Delta i)$				
IIP if evaluated in Model:	Rules ³⁾ optimized in TAYLOR Model			
	2 Parameters	3 Par. (Gap)	3 Par. (Growth)	4 Par. (Gaps)
SW	0.37	0.83	0.01	0.90
ACEL	0.03	0.12	0.01	0.14
Rules optimized in SW Model				
TAYLOR	0.27	0.13	0.03	0.15
ACEL	0.15	0.02	0.01	0.02
Rules optimized in ACEL Model				
SW	0.54	0.11	0.10	0.09
TAYLOR	0.76	0.27	0.25	0.34
Loss($\lambda_y=1$): $Var(\pi) + Var(y) + Var(\Delta i)$				
IIP if evaluated in Model:	Rules optimized in TAYLOR Model			
	2 Parameters	3 Par. (Gap)	3 Par. (Growth)	4 Par. (Gaps)
SW	0.17	5.41	0.66	7.18
ACEL	0.001	M.E. ³⁾	0.31	M.E. ³⁾
Rules optimized in SW Model				
TAYLOR	0.86	3.20	1.05	2.71
ACEL	0.03	0.21	0.44	0.13
Rules optimized in ACEL Model				
SW	0.07	108	1.69	0.53
TAYLOR	0.12	24.9	1.40	3.85

Notes:

¹⁾ The values in this table concern the increase in absolute loss in model Y under a rule optimized for model X relative to a rule of the same class (2-,3-, 4-parameters) optimized in model Y. The increase is measured in terms of the implied inflation (variability) premia proposed by Kuester and Wieland (2010). The IIP corresponds to the increase in the standard deviation of the inflation rate (in percentage point terms) that would imply an equivalent increase in absolute loss.

²⁾ Rules: 2 Parameters: $i_t = \alpha\pi_t + \beta_0 y_t$, 3 Parameters (Gap): $i_t = \rho i_{t-1} + \alpha\pi_t + \beta_0 y_t$;

3 Parameters(Growth): $i_t = \rho i_{t-1} + \alpha\pi_t + \beta_A \Delta y_t$; 4 Parameters (Gaps): $i_t = \rho i_{t-1} + \alpha\pi_t + \beta_0 y_t + \beta_1 y_{t-1}$.

³⁾ M.E. refers to indeterminacy and the existence of multiple self-fulfilling equilibria.

Table 4
Optimized Model-Averaging Rules

Objective: $\text{Min} \sum_{m \in M} \frac{1}{3} (\text{Var}(\pi_m) + \text{Var}(y_m) + \text{Var}(\Delta i_m))$

Rules: $i_t = \rho i_{t-1} + \alpha \pi_t + \beta_0 y_t + \beta_1 y_{t-1} + \beta_\Delta \Delta y_t$

Set of equally-weighted models: $M = \{SW, TAYLOR, ACEL\}$	ρ	α	β_0	β_1	β_Δ
2 Parameters Rule (Gap)		2.75	0.52		
3 Parameters Rule (Gap)	1.05	0.41	0.23		
3 Parameters Rule (Growth)	1.09	0.20			0.76
4 Parameters rule (Gap)	1.06	0.19	0.67	-0.59	

Table 5
Robustness of Model-Averaging Policy Rules
Increase in IIP¹⁾ when a rule optimized in model X is used in model Y
and evaluated relative to the same type of rule optimized in model Y

Loss($\lambda_y=1$): $\text{Var}(\pi) + \text{Var}(y) + \text{Var}(\Delta i)$				
IIP if evaluated in	2 Parameters	3 Par. (Gap)	3 Par. (Growth)	4 Par. (Gaps)
SW	0.11 (1.50) ²⁾	1.02	0.13 (0.84) ²⁾	0.47
TAYLOR	0.03 (2.18) ²⁾	0.56	0.19 (1.71) ²⁾	1.28
ACEL	0.00 (0.17) ²⁾	0.27	0.40 (0.44) ²⁾	0.12

Notes:

¹⁾ The values in this table concern the increase in absolute loss in model Y under a rule optimized by averaging over all models relative to a rule of the same class (2-,3-, 4-parameters) optimized in model Y. The increase is measured in terms of the implied inflation (variability) premia proposed by Kuester and Wieland (2010). The IIP corresponds to the increase in the standard deviation of the inflation rate (in percentage point terms) that would imply an equivalent increase in absolute loss.

²⁾ The values in parenthesis refer to the increase in absolute loss in model Y under a rule optimized by averaging over all models relative to a 4-parameter rule optimized in model Y.

Figure 1
The Effect of a Policy Shock on Interest Rates, Output and Inflation
1 Percentage Point Increase in the Nominal Policy Rate

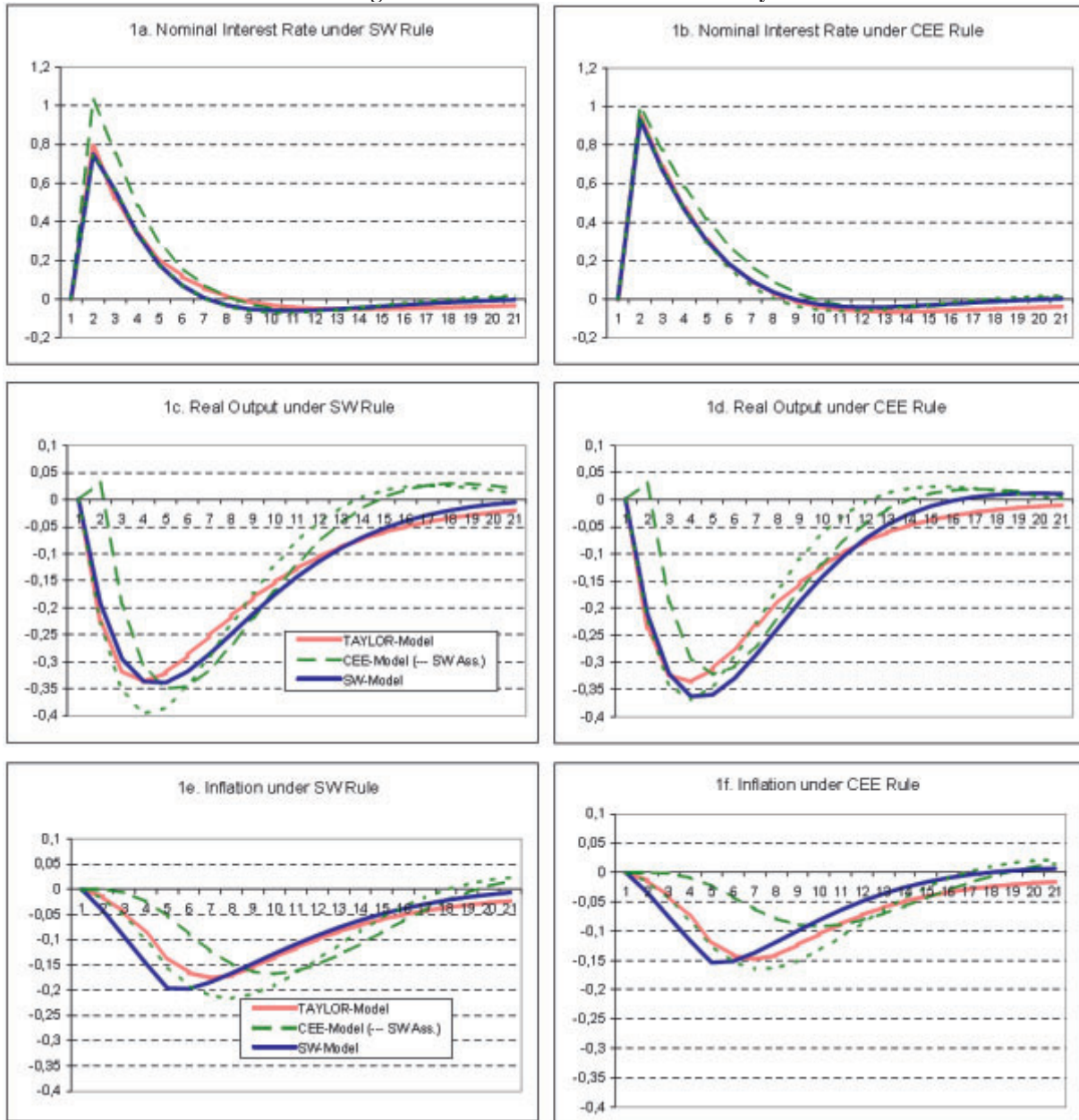


Figure 2
Common Aspects of the Transmission Mechanism in the Three Models (SW Rule)

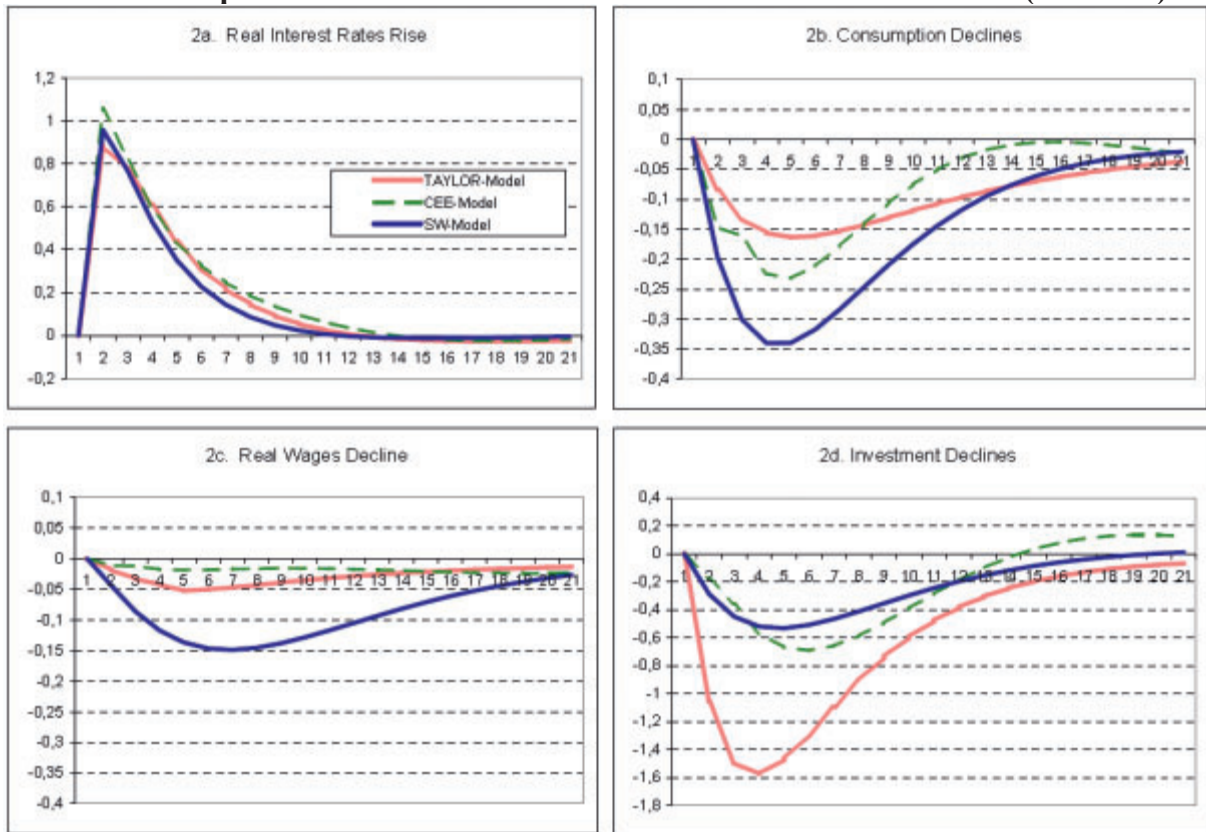
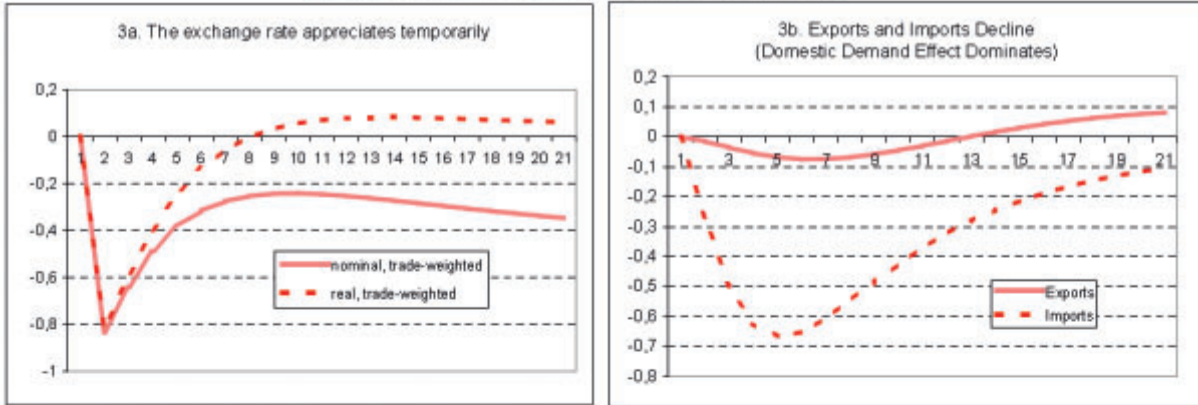


Figure 3
Differences in the Transmission Mechanism in the Three Models (SW Rule)

Only the TAYLOR Model Accounts for International Feedback



Only the SW and CEE Models Account for Labor Supply, Capital Stock and Capital Utilization

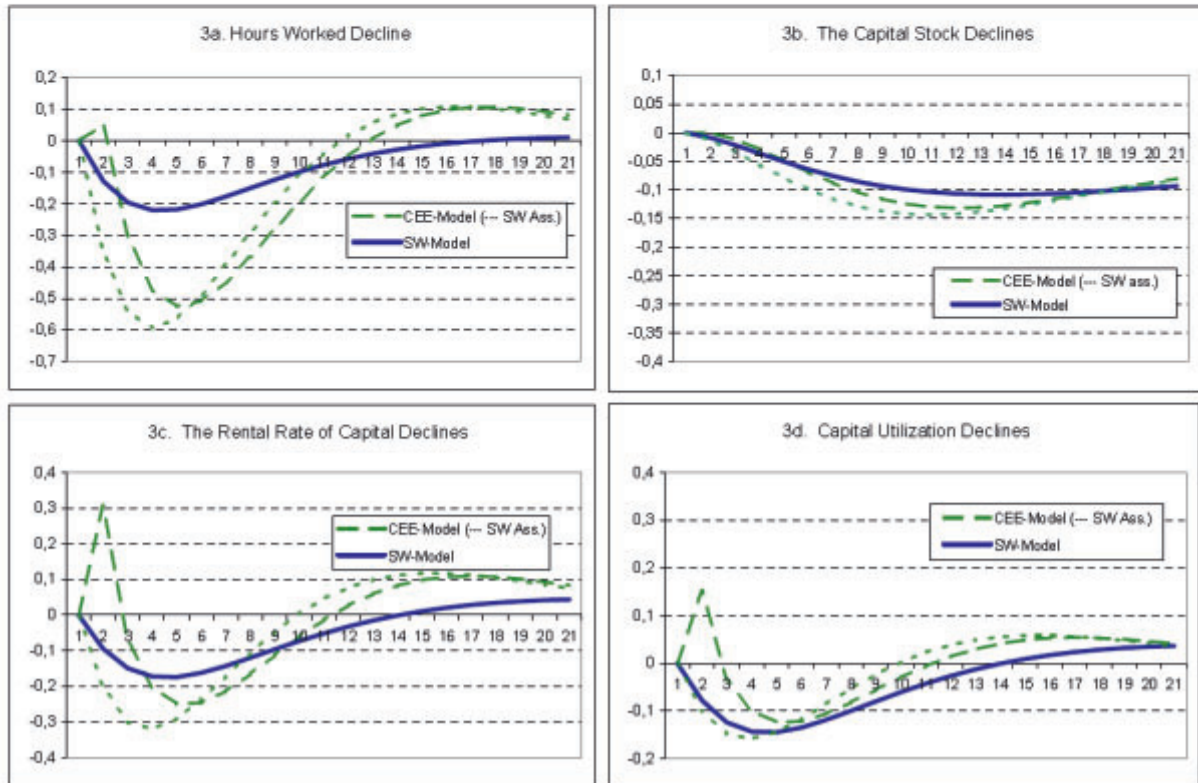


Figure 4
Term Premium Shock in the Taylor and SW Models (SW Rule)
1 Percentage Point Increase in the Term Premium

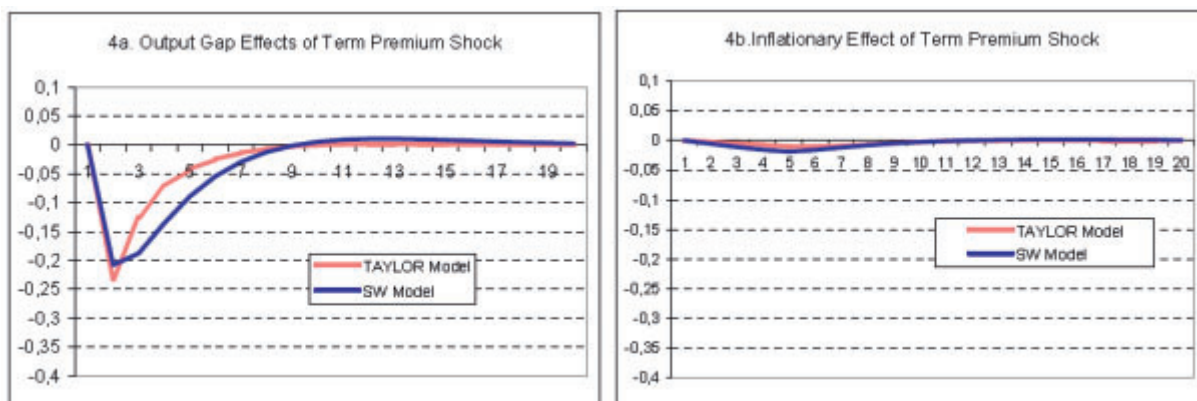


Figure 5
“Demand” Shocks in the Taylor, SW and CEE Models (SW Rule)
1 Percent Increase in the Relevant Variables

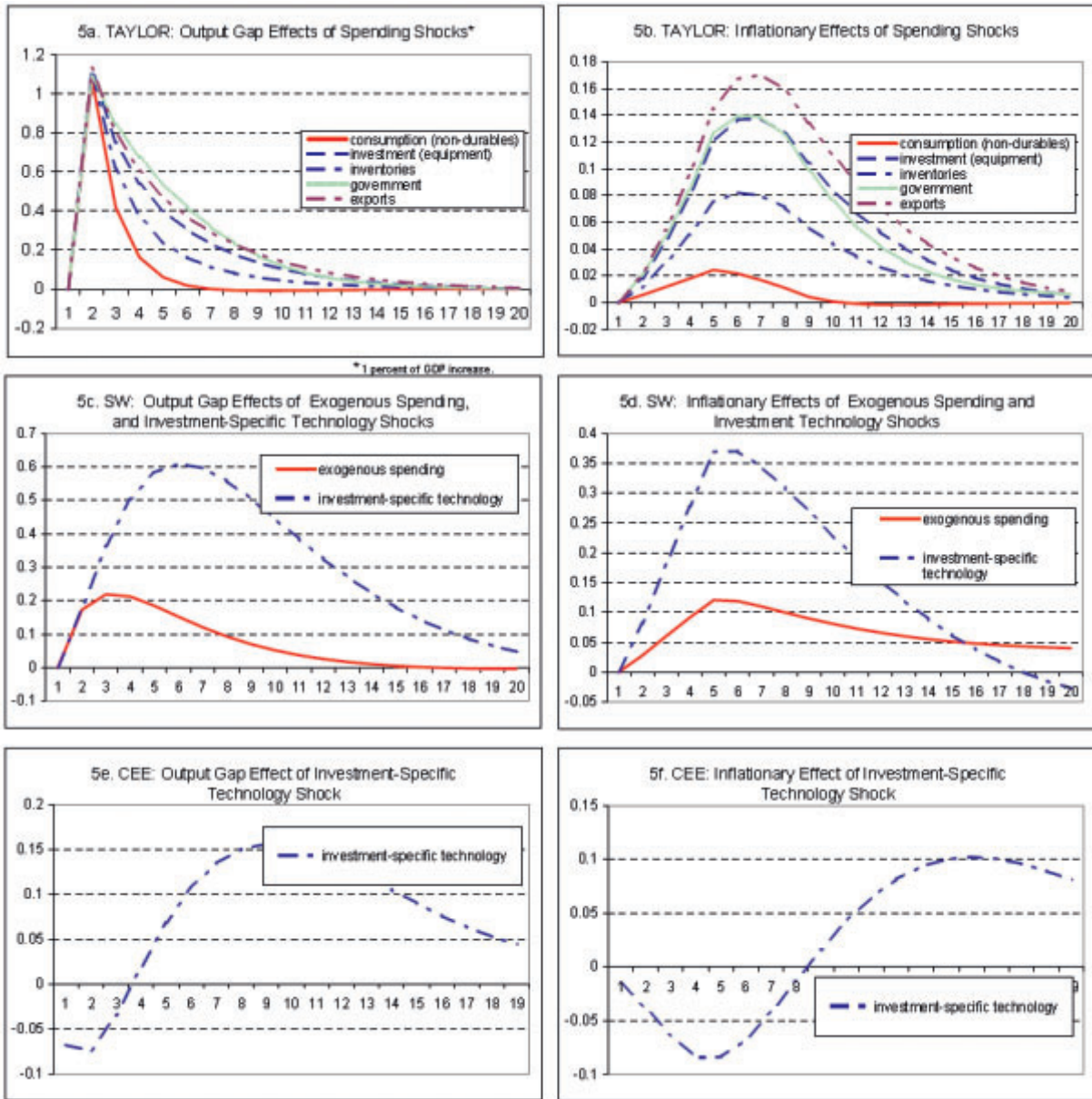
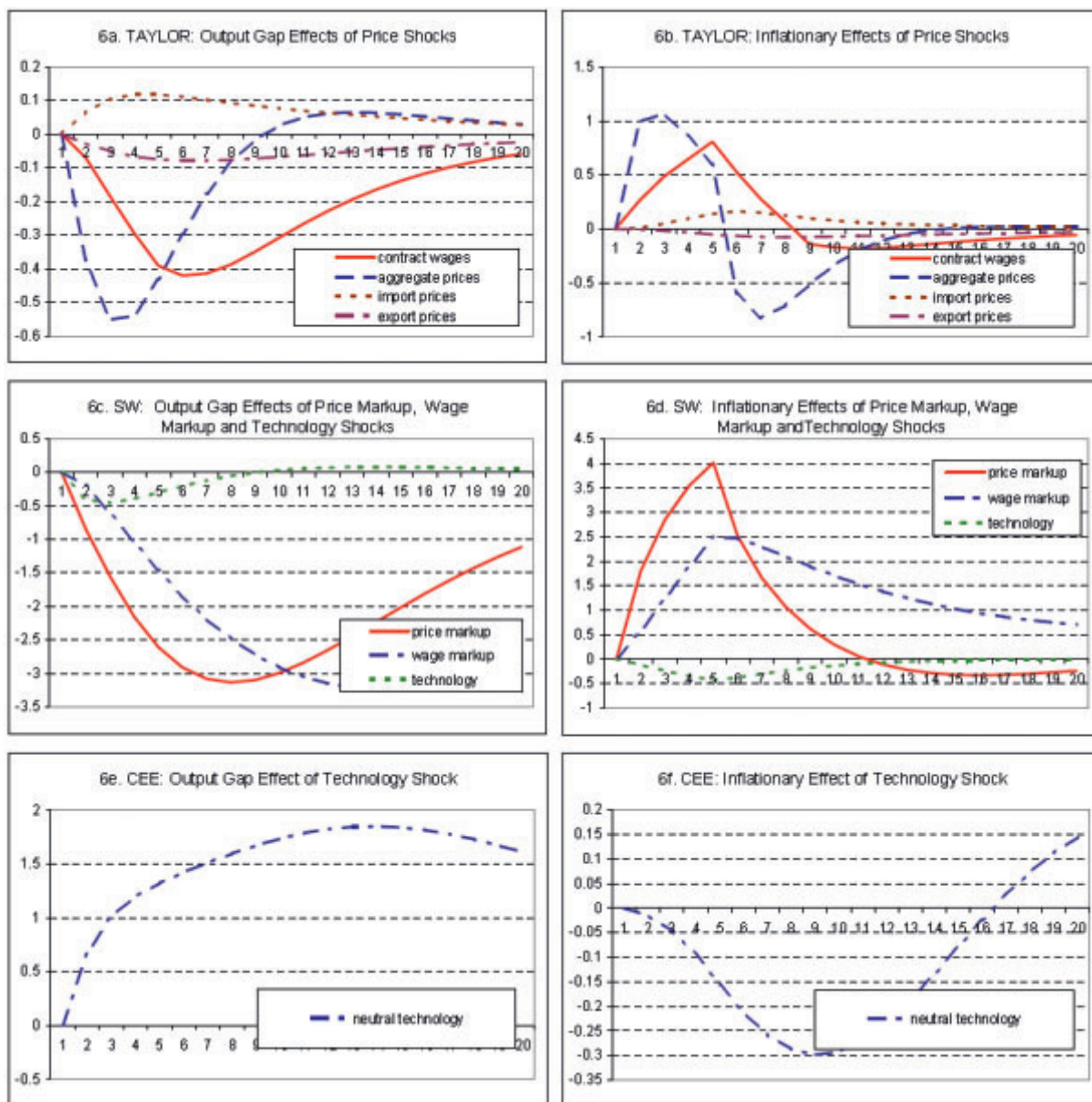


Figure 6
Short-Run and Long-Run “Supply” Shocks in Taylor, SW and CEE Models (SW Rule)
1 Percent Increase in the Relevant Variables



Appendix 1: 35 Models Included in the Model Base as of August 2010¹⁹

1. Small Calibrated Models

1.1 Rotemberg, Woodford (1997)	NK_RW97
1.2 Levin, Wieland, Williams (2003)	NK_LWW03
1.3 Clarida, Gali, Gertler (1999)	NK_CGG99
1.4 Clarida, Gali, Gertler 2-Country (2002)	NK_CGG02
1.5 McCallum, Nelson (1999)	NK_MCN99
1.6 Ireland (2004)	NK_IR04
1.7 Bernanke, Gertler, Gilchrist (1999)	NK_BGG99
1.8 Gali, Monacelli (2005)	NK_GM05

2. Estimated US Models

2.1 Fuhrer, Moore (1995)	US_FM95
2.2 Orphanides, Wieland (1998)	US_OW98
2.3 FRB-US model linearized as in Levin, Wieland, Williams (2003)	US_FRB03
2.4 FRB-US model 08 linearized by Brayton and Laubach (2008)	US_FRB08
2.5 FRB-US model 08 mixed expectations, linearized by Laubach (2008)	US_FRB08mx
2.6 Smets, Wouters (2007)	US_SW07
2.7 CEE/ACEL Altig, Christiano, Eichenbaum, Linde (2004) (m=monetary policy shock, t=technology shock, sw=SW assumptions = no cost channel, no timing constraints)	US_ACELm US_ACELt US_ACELswm US_ACELswt
2.8 New Fed US Model by Edge, Kiley, Laforde (2007)	US_NFED08
2.9 Rudebusch, Svensson (1999)	US_RS99
2.10 Orphanides (2003b)	US_OR03
2.11 IMF projection model by Carabenciov et al. (2008)	US_PM08
2.12 De Graeve (2008)	US_DG08
2.13 Christensen, Dib (2008)	US_CD08
2.14 Iacoviello (2005)	US_IAC05

3. Estimated Euro Area Models

3.1 Coenen, Wieland (2005) (ta: Taylor-staggered contracts)	EA_CW05ta
3.2 Coenen, Wieland (2005) (fm: Fuhrer-Moore staggered contracts)	EA_CW05fm
3.3 ECB Area Wide model linearized as in Dieppe et al. (2005)	EA_AWM05
3.4 Smets, Wouters (2003)	EA_SW03
3.5 Euro Area Model of Sveriges Riksbank (Adolfson et al. 2007)	EA_SR07
3.6 Euro Area Model of the DG-ECFIN EU (Ratto et al. 2009)	EA_QUEST3
3.7 ECB New-Area Wide Model of Coenen, McAdam, Straub (2008)	EA_NAWM08

¹⁹ See Wieland, Cwik, Müller, Schmidt and Wolters (2009) for a detailed exposition of the platform for model comparison. Software and models are available for download from <http://www.macromodelbase.com>.

4. Estimated Small Open-Economy Models (other countries)

- | | |
|--|-----------|
| 4.1. RAMSES Model of Sveriges Riskbank, Adolfson et al.(2008b) | SW_ALLV08 |
| 4.2 Model of the Chilean economy by Medina, Soto (2007) | CL_MS07 |

5. Estimated/Calibrated Multi-Country Models

- | | |
|--|------------|
| 5.1 Taylor (1993a) model of G7 economies | G7_TAY93 |
| 5.2 Coenen,Wieland (2002, 2003) G3 economies | G3_CW03 |
| 5.3 IMF model of euro area & CZrep by Laxton, Pesenti (2003) | EACZ_GEM03 |
| 5.4 FRB-SIGMA model by Erceg, Gust, Guerrieri (2008) | G2_SIGMA08 |

Appendix 2: Additional Sensitivity Studies

This appendix provides material on additional sensitivity studies conducted by the authors that are not included in the printed text of the paper. These findings are summarized at different points throughout the paper. They are organized in the appendix in the same order as they are mentioned in the text under the headings of the relevant sections of the main text.

A-1. Sensitivity studies for “3. Monetary policy shocks in three monetary models of the U.S. economy”

Figures A-1 to A-3 report common aspects and differences regarding the monetary transmission mechanism in the Taylor, SW and CEE/ACEL models under the policy rule used in Christiano, Eichenbaum and Evans (2005). It is referred to as the CEE rule and defined by equation (2) in the main text. The findings should be compared to Figures 2 and 3 in the main text that are obtained under the SW rule (equation 1).

Figure A-1
Common Aspects of the Transmission Mechanism in the Three Models (CEE Rule)

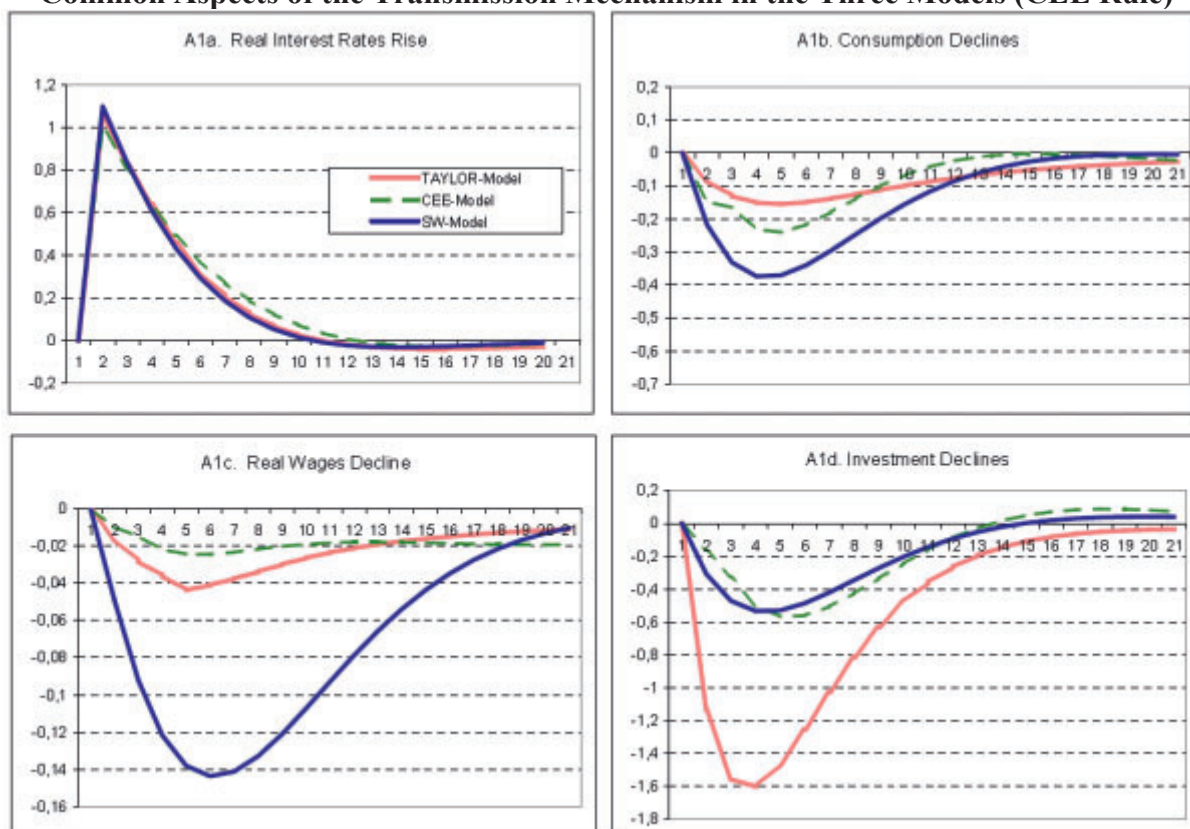


Figure A-2
Only the TAYLOR Model Accounts for International Feedback (CEE Rule)

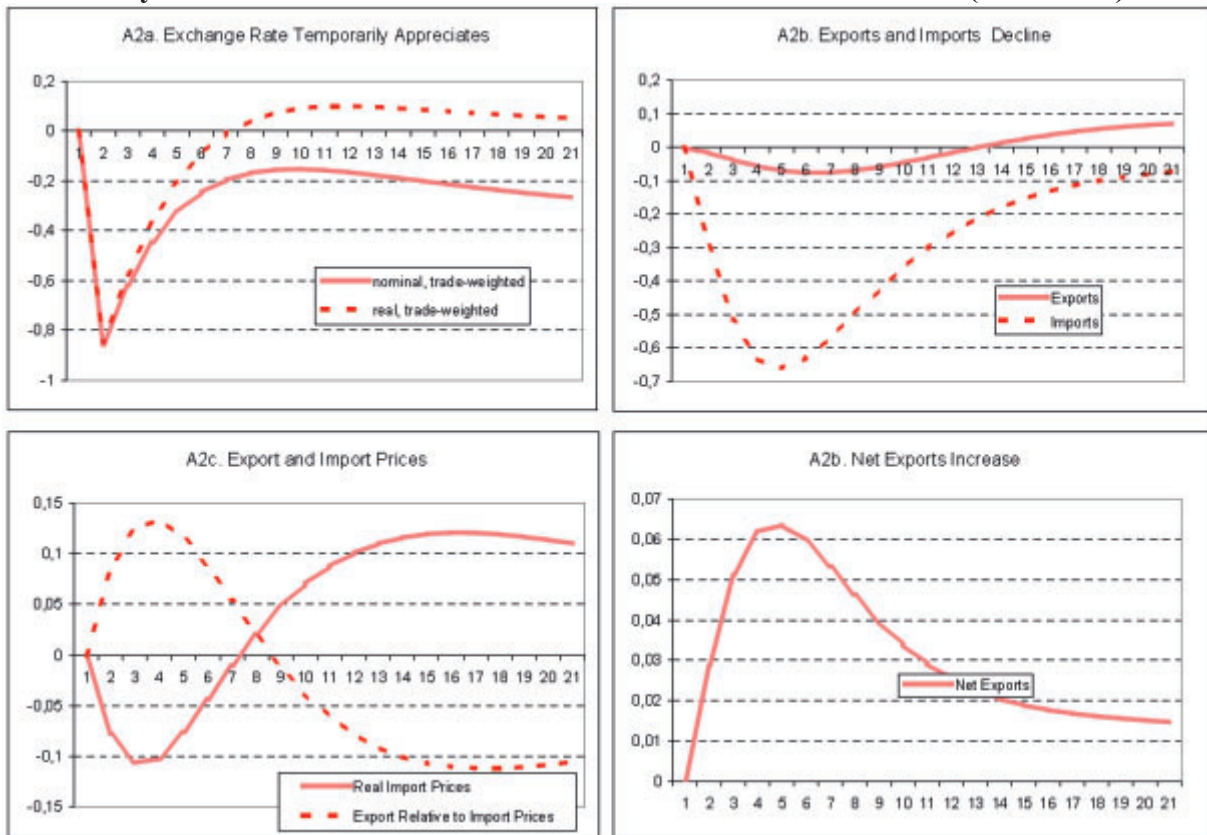
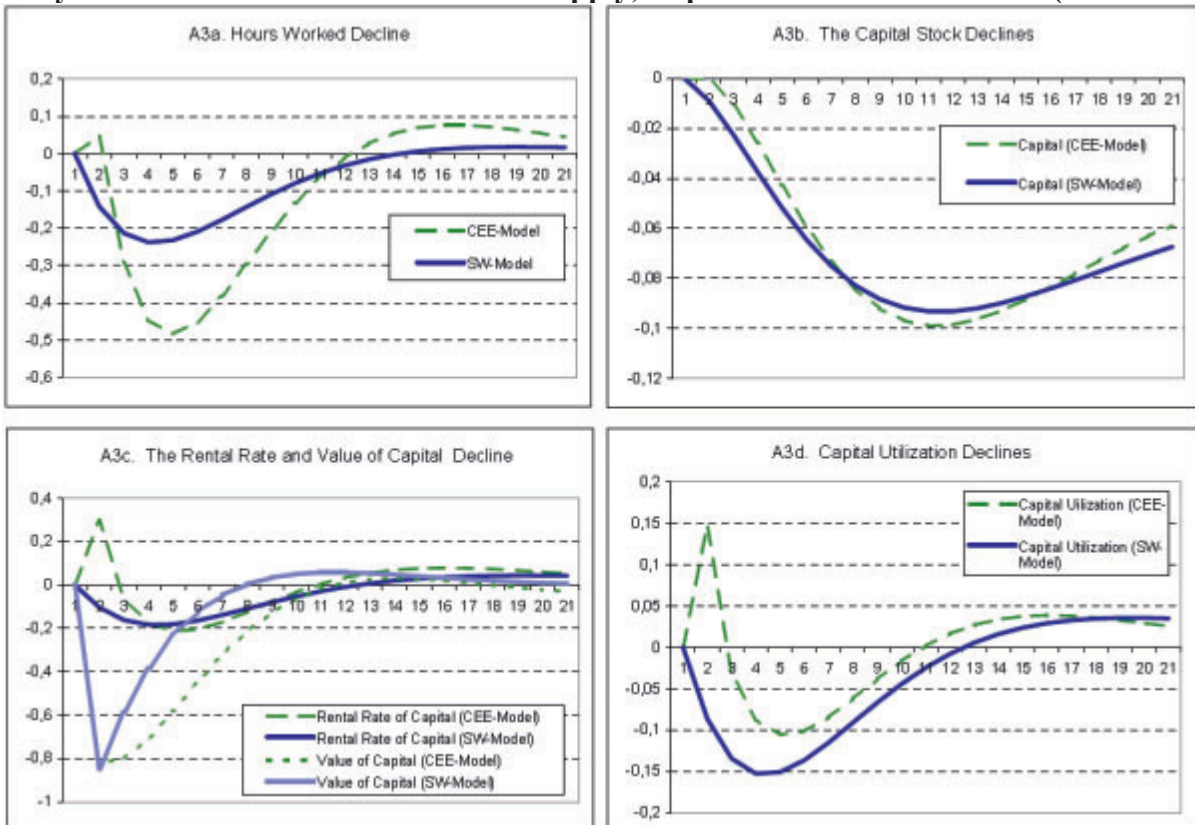


Figure A-3
Only SW and CEE Account for Labor Supply, Capital Stock and Utilization (CEE Rule)



A-2. Sensitivity studies for "5. Optimal simple policy rules in the Taylor, CEE/ACEL and SW models"

Tables A-1 and A-2 provide information on a sensitivity study with a smaller weight of $\lambda_{\Delta i}=0.5$ on the standard deviation of changes in the short-term nominal interest rate. Further sensitivity studies (not reported) were conducted with respect to a weight of 0.5 on the output gap, with respect to the definition of the output gap relative to steady-state output rather than flexible-price output (SW and CEE/ACEL model), and with respect to a version of the CEE/ACEL model with the SW assumptions of no cost-channel and no exogenous delay of the impact of policy. The conclusions discussed in the main text remained the same.

Table A-1
Optimized 2-, 3- and 4-Parameter Rules

$$i_t = \rho i_{t-1} + \alpha \pi_t + \beta_0 y_t + \beta_1 y_{t-1}$$

Rule /Model	Loss ¹⁾ ($\lambda_y = 0, \lambda_{\Delta i} = 0.5$): $Var(\pi) + 0.5Var(\Delta i)$				Loss ($\lambda_y = 1, \lambda_{\Delta i} = 0.5$): $Var(\pi) + Var(y) + 0.5Var(\Delta i)$			
	ρ	α	β_0	β_1	ρ	α	β_0	β_1
	2 Parameters (Gap) ²⁾				$\alpha \pi_t + \beta_0 y_t$			
TAYLOR		3.00	0.22			3.46	0.76	
SW		2.81	-0.12			2.15	0.30	
CEE/ACEL		5.91	0.27			2.87	0.49	
	3 Parameters (Gap)				$\rho i_{t-1} + \alpha \pi_t + \beta_0 y_t$			
TAYLOR	09.7	1.44	0.02		0.97	0.27	0.76	
SW	1.05	0.71	0.01		1.12	0.012	0.015	
CEE/ACEL	0.97	0.99	0.02		2.14	8.29	-1.99	
					(0.01) ³⁾	(2.90) ³⁾	(0.50) ³⁾	
	4 Parameters (Gaps)				$\rho i_{t-1} + \alpha \pi_t + \beta_0 y_t + \beta_1 y_{t-1}$			
TAYLOR	0.98	0.51	0.09	0.02	0.95	0.24	0.60	0.26
SW	1.05	0.65	-0.04	0.05	1.07	0.21	2.22	-2.21
CEE/ACEL	1.01	1.86	0.15	-0.15	1.01	0.75	3.11	-3.18

Notes:

¹⁾ The loss function includes the variance of inflation and the variance of the first-difference of nominal interest rates with a weight of unity, $\lambda_{\Delta i}=1$. λ_y denotes the weight on the variance of the output gap.

²⁾ In the Taylor model the output gap denotes the difference between actual and trend output. In the SW and ACEL models it is the difference to the level realized under flexible prices given current macroeconomic shocks.

³⁾ The ACEL model, which has only two shocks, exhibits only very small values of the loss function and multiple local optima. For example, a local optimum with much smaller parameter values is displayed in parentheses.

Table A-2
Increase in Loss when Reducing the Number of Parameters in the Rule
 Percentage Increase (Increase in IIP)¹⁾

Models	Loss ($\lambda_y = 0 \lambda_{\Delta i} = 0.5$): $Var(\pi) + 0.5Var(\Delta i)$	
	4 versus 3 Parameters (Gaps)	3 versus 2 Parameters (Gaps)
TAYLOR	0.10% (0.001)	210% (1.04)
SW	0.26% (0.001)	253% (0.62)
CEE/ACEL	3.51% (0.001)	217% (0.03)
	Loss($\lambda_y = 1 \lambda_{\Delta i} = 0.5$): $Var(\pi) + Var(y) + 0.5Var(\Delta i)$	
TAYLOR	1.78% (0.06)	88.0% (1.81)
SW	12.4% (0.53)	23.7% (1.10)
CEE/ACEL	13.7% (0.10)	11.18% (0.12)

Notes:

¹⁾The values in parentheses measure the increase in absolute loss in terms of the implied inflation (variability) premia proposed by Kuester and Wieland (2010). The IIP corresponds to the increase in the standard deviation of the inflation rate (in percentage point terms) that would imply an equivalent increase in absolute loss.

Because of the odd properties exhibited by the ACEL model in the policy optimization (specifically the existence of multiple local optima) we investigated whether a small number of shocks would induce similar properties in the policy optimization with the SW model. The ACEL model has a monetary policy shock (which is turned off in the optimization), and investment-specific technology shock and a neutral technology shock. The SW model also has an investment-specific and a neutral technology shock in addition to other shocks. Thus, we have shut down these other shocks in the SW model and re-optimized the policy rules in the SW model with only the two technology shocks. The findings are reported in Table A-3 in comparison to the other rules reported previously in Table 1 in the paper. The weight on interest volatility, $\lambda_{\Delta i}$, is set to unity as in the main text of the paper. The optimized rules in the SW model change, but they do not approach the extreme values found in the ACEL model, nor does the computation exhibit multiple local optima. Other features of the ACEL model must be at the root of these findings. Thus, we keep the ACEL in the optimization and robustness exercise.

Table A-3
Optimal Simple Policy Rules¹⁾
with Shocks in SW turned off to compare to ACEL

Rules: $i_t = \rho i_{t-1} + \alpha \pi_t + \beta_0 y_t + \beta_1 y_{t-1}$

Rule /Model	Loss ($\lambda_y = 0$): $Var(\pi) + Var(\Delta i)$				Loss ($\lambda_y = 1$): $Var(\pi) + Var(y) + Var(\Delta i)$			
	ρ	α	β_0	β_1	ρ	α	β_0	β_1
	2 Parameters (Gap) ²⁾				$\alpha \pi_t + \beta_0 y_t$			
SW		2.33	-0.10			2.04	0.26	
CEE/ACEL		4.45	0.28			2.57	0.45	
SW/2 shocks		5.07	-0.29			5.12	1.08	
	3 Parameters (Gap)				$\rho i_{t-1} + \alpha \pi_t + \beta_0 y_t$			
SW	1.06	0.49	0.01		1.13	0.012	0.015	
CEE/ACEL	0.97	0.99	0.02		2.84	7.85	-2.12	
SW/2 shocks	1.07	0.89	0.03		1.02	0.35	0.87	
	4 Parameters (Gaps)				$\rho i_{t-1} + \alpha \pi_t + \beta_0 y_t + \beta_1 y_{t-1}$			
SW	1.06	0.46	-0.03	0.03	1.07	0.16	1.63	-1.62
CEE/ACEL	1.01	1.11	0.18	-0.18	1.04	0.51	2.24	-2.30
SW/2 shocks	1.08	0.96	0.11	-0.10	1.02	0.42	1.09	-0.29

Notes:

¹⁾ The loss function includes the variance of inflation and the variance of the first-difference of nominal interest rates with a weight of unity, $\lambda_{\Delta i}=1$. λ_y denotes the weight on the variance of the output gap.

²⁾ In the Taylor model the output gap denotes the difference between actual and trend output. In the SW and ACEL models it is the difference to the level realized under flexible prices given current macroeconomic shocks.

A-3. Sensitivity studies for "6. Robustness"

Table A-3 provide information on a sensitivity study with a smaller weight of $\lambda_{\Delta i}=0.5$ on the standard deviation of changes in the short-term nominal interest rate. The findings should be compared to Table 3 in the main text of the paper. The conclusions discussed in the main text remain the same.

Table A-4

Robustness of Policy Rules

Increase in IIP¹⁾ when a rule optimized in model X is used in model Y and evaluated relative to a rule optimized in model Y.

Loss ($\lambda_y=0, \lambda_{\Delta i}=0.5$): $Var(\pi) + 0.5Var(\Delta i)$			
IIP if evaluated in Model:	Rules ³⁾ optimized in TAYLOR Model		
	2 Parameters	3 Parameters (Gap)	4 Parameters (Gaps)
SW	0.34	0.70	0.77
ACEL	0.02	0.11	0.12
Rules optimized in SW Model			
TAYLOR	0.19	0.12	0.77
ACEL	0.11	0.01	0.12
Rules optimized in ACEL Model			
SW	0.47	0.10	0.12
TAYLOR	0.82	0.28	0.46
Loss($\lambda_y=1, \lambda_{\Delta i}=0.5$): $Var(\pi) + Var(y) + 0.5Var(\Delta i)$			
IIP if evaluated in Model:	Rules optimized in TAYLOR Model		
	2 Parameters	3 Parameters (Gap)	4 Parameters (Gaps)
SW	0.18	6.04	7.63
ACEL	0.02	M.E. ³⁾	M.E. ³⁾
Rules optimized in SW Model			
TAYLOR	1.09	3.36	2.39
ACEL	0.02	0.23	0.13
Rules optimized in ACEL Model			
SW	0.08	55.4	0.54
TAYLOR	0.27	24.4	3.57

Notes:

¹⁾ The values in this table concern the increase in absolute loss in model Y under a rule optimized for model X relative to a rule of the same class (2-,3-, 4-parameters) optimized in model Y. The increase is measured in terms of the implied inflation (variability) premia proposed by Kuester and Wieland (2010). The IIP corresponds to the increase in the standard deviation of the inflation rate (in percentage point terms) that would imply an equivalent increase in absolute loss.

²⁾ Rules: 2 Parameters: $i_t = \alpha\pi_t + \beta_0 y_t$, 3 Parameters (Gap): $i_t = \rho i_{t-1} + \alpha\pi_t + \beta_0 y_t$;

3 Parameters (Growth),: $i_t = \rho i_{t-1} + \alpha\pi_t + \beta_A \Delta y_t$; 4 Parameters (Gaps): $i_t = \rho i_{t-1} + \alpha\pi_t + \beta_0 y_t + \beta_1 y_{t-1}$.

³⁾ M.E. refers to indeterminacy and the existence of multiple self-fulfilling equilibria.

A-4. Sensitivity studies for "7. Conclusions and extensions / Utility Based Loss Functions"

We have computed optimized policy rules for the following quadratic approximation of the unconditional expectation of consumer welfare in the model of Smets and Wouters (2003) derived in the working paper version of Onatski and Williams (2004):

$$\begin{aligned}
 L &= L_{\text{Onatski-Williams}(2004)} + \text{Var}(\Delta i) \\
 &= \text{Var}(\pi_t) + 0.21\text{Var}(K_{t-1}) - 0.51\text{Cov}(\pi_t, \pi_{t-1}) + 0.24\text{Var}(w_t) \\
 &\quad + 0.24\text{Cov}(w_t, \pi_t) - 0.24\text{Cov}(w_t, w_{t-1}) - 0.24\text{Cov}(\pi_t, w_{t-1}) \\
 &\quad + \text{Var}(\Delta i)
 \end{aligned}$$

We have added $\text{Var}(\Delta i)$ to the loss function to account for central bank's tendency to keep interest rate volatility in check and avoid regular violations of the non-negativity constraint on nominal interest rates. The optimized 2-, 3- and 4-parameter rules are reported in Table A-5. The robustness of rules derived under the simpler loss function is evaluated in Table A-6. As noted in the main text, 2-parameter rules with inflation and the output gap and 3-parameter rules with interest rate smoothing that replace the output gap with the deviation of output growth from trend are quite robust, but not the other rules.

Table A-5
Optimized Rules in SW Model
 $L = L_{\text{Onatski-Williams}(2004)} + \text{Var}(\Delta i)$

Utility-Based Loss	ρ	α	β_0	β_1	β_Δ	Loss
4 Parameter Rule (Gaps)	0.97	0.52	0.60	-0.52		22.97
3 Parameter Rule (Gap)	0.76	0.89	0.11	-		23.00
2 Parameter Rule (Gap)	-	2.55	0.17	-		23.54
3 Parameters Rule (Growth)	1.14	0.16			0.53	22.17

Table A-6

Performance and Robustness of Rules with Utility-Based Loss

Compare the performance and robustness of rules optimized under the simple New-Keynesian (NK) loss function relative to the SW model utility-based loss function of Onatski and Williams (2004).

Rule	Loss
4 Parameter Rules (Gaps)	
Benchmark:	
SW Model, SW-Loss	22.97
SW, NK-Loss	26.02
TAYLOR, NK-Loss	110.8
ACEL, NK-Loss	24.91
3 Parameter Rules (Gap)	
Benchmark:	
SW Model, SW-Loss	23.0
SW, NK-Loss	25.08
TAYLOR, NK-Loss	79.88
ACEL, NK-Loss	4956
2 Parameter Rules (Gap)	
Benchmark:	
SW Model, SW-Loss	23.54
SW, NK-Loss	24.28
TAYLOR, NK-Loss	24.13
ACEL, NK-Loss	24.29
3 Parameter Rules (Growth)	
Benchmark:	
SW Model, SW-Loss	22.17
SW, NK-Loss	23.25
TAYLOR, NK-Loss	22.71
ACEL, NK-Loss	24.57

A-5. Sensitivity studies for "7. Conclusions and extensions / Robustness to other macroeconomic models"

We have extended our analysis of the performance and robustness of simple monetary policy rules by including the estimated DSGE model of the U.S. economy of De Graeve (2008) (DG Model in the following). This model includes a more detailed financial sector through a financial accelerator mechanism. The GDP response to a monetary policy shock remains very similar to the findings in Figure 1 in the main text (see Figure A4 below). As noted in the main text 2-parameter rules optimized in the DG model are not very robust to the other models. However, the model-averaging rules are still very robust when the DG model is included in the optimization, and remain very close to the model-averaging rules obtained with only three models. See Tables A7 to A11, which show the results with the DG model in comparison to the results with the other models reported previously in Tables 1 to 5 in the main text.

Figure A-4
Monetary policy shock under SW Rule in 4 Models

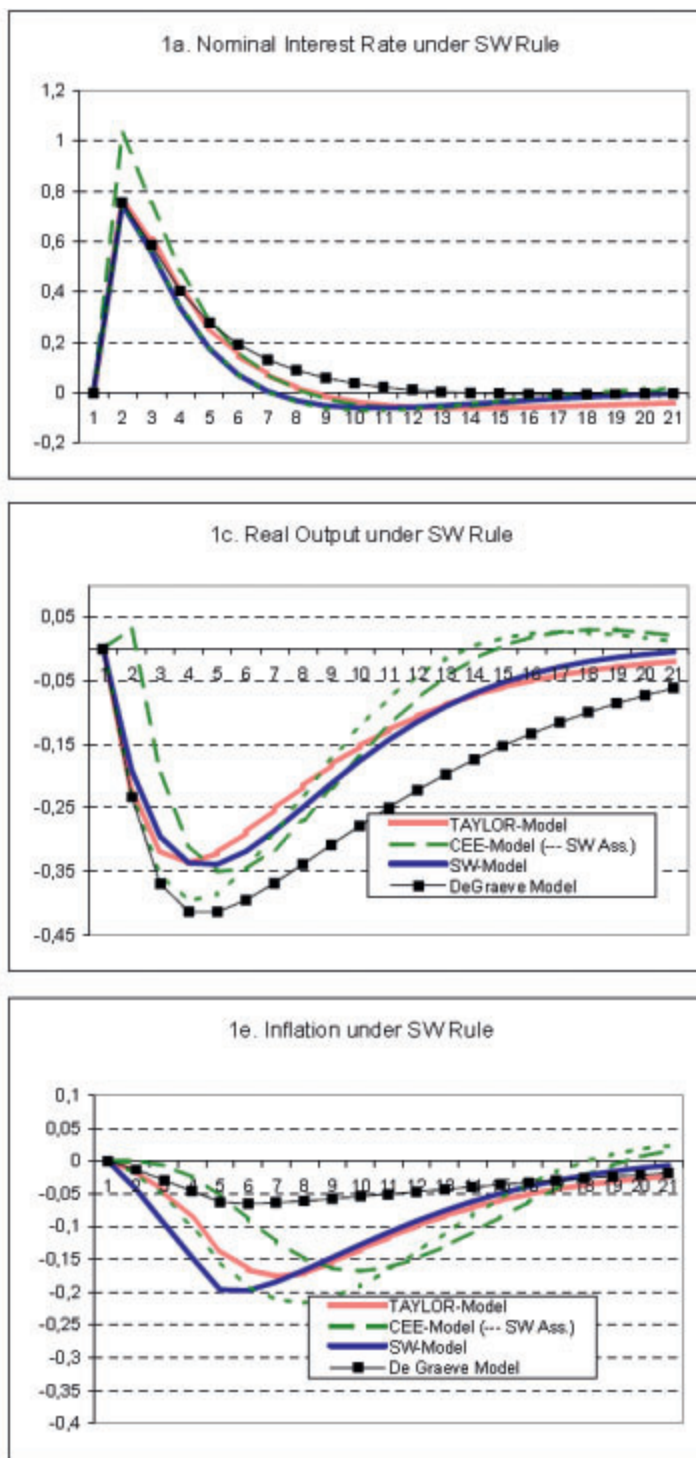


Table A-7
Optimal Simple Policy Rules¹⁾

Rules: $i_t = \rho i_{t-1} + \alpha \pi_t + \beta_0 y_t + \beta_1 y_{t-1} + \beta_\Delta \Delta y_t$

Rule /Model	Loss ($\lambda_y = 0$): $Var(\pi) + Var(\Delta i)$					Loss ($\lambda_y = 1$): $Var(\pi) + Var(y) + Var(\Delta i)$				
	ρ	α	β_0	β_1	β_Δ	ρ	α	β_0	β_1	β_Δ
	2 Parameters (Gap) ²⁾					$\alpha \pi_t + \beta_0 y_t$				
TAYLOR		2.54	0.19				3.00	0.52		
SW		2.33	-0.10				2.04	0.26		
CEE/ACEL		4.45	0.28				2.57	0.45		
DG		1.34	0.31				1.51	0.60		
	3 Parameters (Gap)					$\rho i_{t-1} + \alpha \pi_t + \beta_0 y_t$				
TAYLOR	0.98	0.37	0.09			0.98	0.21	0.53		
SW	1.06	0.49	0.01			1.13	0.012	0.015		
CEE/ACEL	0.97	0.99	0.02			2.84	7.85	-2.12		
DG	0.99	0.30	0.01			0.95	0.35	0.15		
	4 Parameters (Gaps)					$\rho i_{t-1} + \alpha \pi_t + \beta_0 y_t + \beta_1 y_{t-1}$				
TAYLOR	0.98	0.37	0.07	0.02		0.96	0.18	0.41	0.19	
SW	1.06	0.46	-0.03	0.03		1.07	0.16	1.63	-1.62	
CEE/ACEL	1.01	1.11	0.18	-0.18		1.04	0.51	2.24	-2.30	
DG	0.99	0.30	0.04	-0.03		0.90	0.34	-0.24	0.40	
	3 Parameters (Growth) ³⁾					$\rho i_{t-1} + \alpha \pi_t + \beta_\Delta \Delta y_t$				
TAYLOR	1.01	0.52			0.07	1.13	0.40			0.68
SW	1.03	0.48			-0.01	1.01	0.20			1.04
CEE/ACEL	1.02	1.07			-0.002	0	3.71			.002
DG	1.00	0.30			-0.002	0.83	0.47			-0.02

Notes:

¹⁾ The loss function includes the variance of inflation and the variance of the first-difference of nominal interest rates with a weight of unity, $\lambda_{\Delta i}=1$. λ_y denotes the weight on the variance of the output gap.

²⁾ In the Taylor model the output gap denotes the difference between actual and trend output. In the SW and ACEL models it is the difference to the level realized under flexible prices given current macroeconomic shocks.

³⁾ The output growth measure Δy_t is defined relative to steady-state/trend output growth in all three models.

Table A-8
Increase in Loss when Reducing the Number of Parameters in the Rule
 Percentage Increase (Increase in IIP)¹⁾

Models	Loss ($\lambda_y = 0$): $Var(\pi) + Var(\Delta i)$		
	4 versus 3 Parameters (Gaps)	4 Parameters (Gaps) vs 3 Par. (Growth)	3 versus 2 Parameters (Gaps)
TAYLOR	0.12% (0.001)	13.5% (0.10)	278% (1.38)
SW	0.22% (0.001)	1.40% (0.01)	316% (0.78)
CEE/ACEL	5.10% (0.001)	10.0% (0.003)	229% (0.04)
DG	0.23%(0.001)	2.64% (0.01)	147% (0.35)
	Loss($\lambda_y = 1$): $Var(\pi) + Var(y) + Var(\Delta i)$		
TAYLOR	1.81% (0.07)	67.1% (1.61)	98.8% (2.14)
SW	10.6% (0.47)	18.1% (0.76)	25.6% (1.17)
CEE/ACEL	14.4% (0.11)	36.7% (0.22)	9.67% (0.11)
DG	1.2% (0.04)	44.5% (0.91)	23.5%(0.57)

Notes:

¹⁾The values in parentheses measure the increase in absolute loss in terms of the implied inflation (variability) premia proposed by Kuester and Wieland (2010). The IIP corresponds to the increase in the standard deviation of the inflation rate (in percentage point terms) that would imply an equivalent increase in absolute loss.

Table A-9
Robustness of Policy Rules
 Increase in IIP¹⁾ when a rule optimized in model X is used in model Y
 relative to rule optimized in model Y.

Loss ($\lambda_y=0$): $Var(\pi) + Var(\Delta i)$				
IIP if evaluated in Model:	Rules optimized in TAYLOR Model			
	2 Parameters	3 Par. (Gap)	3 Par. (Growth)	4 Par. (Gaps)
SW	0.37	0.83	0.01	0.90
ACEL	0.03	0.12	0.01	0.14
DG	0.23	0.13	0.02	0.14
Rules optimized in SW Model				
TAYLOR	0.27	0.13	0.03	0.15
ACEL	0.15	0.02	0.01	0.02
DG	M.E. ²⁾	0.05	0.03	0.28
Rules optimized in ACEL Model				
SW	0.54	0.11	0.10	0.09
TAYLOR	0.76	0.27	0.25	0.34
DG	0.80	0.16	0.19	0.14
Rules optimized in DG Model				
TAYLOR	1.14 (2.30) ³⁾	0.16	0.11	0.15
SW	3.20 (3.73) ³⁾	0.11	0.03	0.11
ACEL	0.17	0.02	0.03	0.02
Loss ($\lambda_y=1$): $Var(\pi) + Var(y) + Var(\Delta i)$				
IIP if evaluated in:	Rules optimized in TAYLOR Model			
	2 Parameters	3 Par. (Gap)	3 Par. (Growth)	4 Par. (Gaps)
SW	0.17 (1.53) ³⁾	5.41	0.66 (1.21) ³⁾	7.18
ACEL	0.001	M.E. ²⁾	0.31	M.E. ²⁾
DG	0.40	2.07	0.87	2.31
Rules optimized in SW Model				
TAYLOR	0.86 (2.64) ³⁾	3.20	1.05 (2.28) ³⁾	2.71
ACEL	0.03	0.21	0.44	0.13
DG	0.29	5.39	1.27	0.28
Rules optimized in ACEL Model				
SW	0.07	108	1.69	0.53
TAYLOR	0.12	24.9	1.40	3.85
DG	0.28	15.1	0.88	0.72
Rules optimized in DG Model				
TAYLOR	1.23 (2.89) ³⁾	1.08	1.97	1.56
SW	2.09 (2.88) ³⁾	0.96	1.54	1.74
ACEL	0.27	0.20	0.18	0.34

Notes:

¹⁾The values in this table concern the increase in absolute loss under a particular rule relative to the comparable simple policy rule optimized in the respective model. The increase is measured in terms of the implied inflation (variability) premia proposed by Kuester and Wieland (2010). The IIP corresponds to the increase in the standard deviation of the inflation rate (in percentage point terms) that would imply an equivalent increase in absolute loss.

²⁾M.E. refers to indeterminacy and the existence of multiple self-fulfilling equilibria.

³⁾The values in parenthesis refer to the IIP that results from implementing the rule optimized in one model in any of the other model and comparing the generated loss to the loss that would be realized under 4-parameter rule optimized for that specific model.

Table A-10

Optimized Model-Averaging Rules

Objective: $\text{Min} \sum_{m \in M} \frac{1}{4} (\text{Var}(\pi_m) + \text{Var}(y_m) + \text{Var}(\Delta i_m))$

Rules: $i_t = \rho i_{t-1} + \alpha \pi_t + \beta_0 y_t + \beta_1 y_{t-1} + \beta_\Delta \Delta y_t$

Set of equally-weighted models: $M = \{SW, TAYLOR, ACEL, DG\}$	ρ	α	β_0	β_1	β_Δ
2 Parameters Rule (Gap)		2.64	0.53		
3 Parameters Rule (Gap)	1.03	0.42	0.22		
3 Parameters Rule (Growth)	1.09	0.25			0.72
4 Parameters rule (Gap)	1.06	0.21	0.68	-0.60	

Table A-11
Robustness of Model-Averaging Policy Rules (IIP¹)

Loss($\lambda_y=1$): $\text{Var}(\pi) + \text{Var}(y) + \text{Var}(\Delta i)$				
IIP if evaluated in	2 Parameters	3 Par. (Gap)	3 Par. (Growth)	4 Par. (Gaps)
SW	0.10 (1.49) ²	1.01	0.27 (0.94) ²	0.48
TAYLOR	0.06 (2.19) ²	0.59	0.13 (1.68) ²	1.28
ACEL	0.01 (0.17) ²	0.25	0.35 (0.41) ²	0.16
DG	0.27 (0.75) ²	0.11	0.99 (1.47) ²	0.19

Notes:

¹) The values in this table concern the increase in absolute loss in model Y under a rule optimized by averaging over all models relative to a rule of the same class (2-,3-, 4-parameters) optimized in model Y. The increase is measured in terms of the implied inflation (variability) premia proposed by Kuester and Wieland (2010). The IIP corresponds to the increase in the standard deviation of the inflation rate (in percentage point terms) that would imply an equivalent increase in absolute loss.

²) The values in parentheses refer to the increase in absolute loss in model Y under a rule optimized by averaging over all models relative to a 4-parameter rule optimized in model Y.

