Toward a Taylor Rule for Fiscal Policy*

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May 2, 2011

Abstract

This paper presents a procedure to determine simple policy feedback rules in dynamic stochastic general equilibrium (DSGE) models with respect to the policymaker's objective function. We illustrate our approach with fiscal feedback rules for tax instruments in a standard medium-scale DSGE model. First, we approximate the optimal dynamic behavior of the economy using simple linear feedback rules. Then, we calculate the elasticities of the moments of welfare with respect to the feedback coefficients. The feedback coefficients associated with the highest elasticities form the policy feedback rules. Afterwards, we confirm their empirical validity.

JEL classification: E62, H30, C51.

Keywords: Fiscal policy, Bayesian model estimation, Identification

*We would like to thank Giancarlo Corsetti, Wouter denHaan, Dale Henderson, Mathias Hoffmann, Tatjana Kirsinova, Jenny Kragl, Michael Krause, Thomas Laubach, Bartosz Mackowiak, Alexander Meyer-Gohde, Tommaso Monacelli, Stephane Moyen, Gernot Müller, Morten Ravn, Christian Stoltenberg, Mathias Trabandt, Lutz Weinke, and Alexander Wolman for their helpful comments. Moreover, we would like to thank seminar participants and discussants at the 6th Dynare Conference in Helsinki, the 44th Canadian Economic Association in Quebec, the 16th International Conference of the Society of Computational Economics in London, the Verein für Socialpolik in Kiel, the University of Münster, the Bundesbank, and the ECB for their helpful comments. An earlier version of this paper was circulating under the title "Implementable Fiscal Policy Rules". The views expressed by the authors in this paper are their own and do not necessarily reflect those of the Deutsche Bundesbank.

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1 Introduction

In recent empirical work, Taylor (2000) and Auerbach (2002) provide evidence that there is an endogenous response of fiscal policy instruments to business cycles. In a dynamic stochastic general equilibrium (DSGE) model, the literature has started to model this endogenous response by policy feedback rules. So far, there is no agreement how these rules should be specified. For this reason, the rules are often modeled as simple ad-hoc processes (Leeper, Plante, and Traum, 2010; Forni, Monteforte, and Sessa, 2009). This approach is inconsistent with the typical assumptions for the remaining sectors in the economy, where their dynamic behavior is based on the solutions to their respective optimization problems. Hence households, firms, and the monetary policy authority act purposefully[1] while the fiscal policy sector does not. In that respect, characterizing a fiscal policy sector by ad-hoc rules constitutes a not at all satisfying approach.

A straightforward solution to this issue is to postulate a social planner as a purposeful fiscal policy maker. This assumption involves very complex reaction functions. Additionally, for an empirical validation assuming an optimal policy maker is difficult to maintain. For instance, optimal fiscal policy in general implies subsidies for capital and the complex policy reaction functions are not identifiable. For that reason the policy maker's optimal behavior is approximated by simple feedback rules similar to Schmitt-Grohé and Uribe (2007). But still, it is not clear how these simple rules should be specified, i.e. which variables should be included in these rules. This paper presents a procedure to select these variables.

The key assumption in our setup is to include those feedback variables which influence welfare most at the optimal allocation. To calculate the welfare-maximizing fiscal policy, we characterize the private sector by the solution to the households' and firms' problems and the corresponding structural model parameters. We use Bayesian estimation techniques

[1] The empirically observed Taylor-type rule itself is not optimal but its feedback variables are the correct choice of a welfare-maximizing policy maker. See e.g. Woodford (2003) for a discussion and evaluation of optimal feedback rules under commitment. For this reason we classify monetary policy in common DSGE models as purposeful rather than ad-hoc.

to parameterize the private sector. Since the optimal policy reaction functions are highly non-linear and complex, we approximate them using simple, linear feedback rules. These feedback rules include a wide variety of feedback variables. We compute the elasticities of the model welfare's moments with respect to the feedback coefficients in the policy rules. This allows us to identify and rank the feedback variables according to their importance for the optimal dynamic behavior of welfare. Then, the simple policy feedback rules are determined by picking the most important feedback variables for each policy instrument with respect to welfare. Finally, we re-estimate the DSGE model including the previously derived policy rules. This is necessary to check the policy invariance of the private sector estimates and to verify the empirical relevance of the selected feedback variables. These policy rules represent a further step toward empirically and theoretically founded fiscal feedback rules - similar to the standard Taylor rule in monetary economics.

The approach in this paper is applicable to various policy feedback rules. In our application, we determine the feedback rules for taxes on capital income and labor income within a standard medium-scale DSGE model such as that proposed by Schmitt-Grohé and Uribe (2006, 2007). In particular, for both tax rates, we identify government debt and lagged tax rates as being important for the welfare's variance and therefore include these variables in the feedback rules. For the same reason, the labor income tax rule additionally includes a feedback coefficient on hours worked and the capital income tax rule contains a feedback coefficient on investment.

When estimating the model closed by these policy feedback rules, we identify all policy coefficients and estimate them significantly different from zero. While both estimated feedback rules contain pro-cyclical as well as counter-cyclical fiscal policy elements, the estimated impulse response functions imply counter-cyclical fiscal policy. Both tax rates rise during a boom. This finding emphasizes the importance of carefully modeled fiscal feedback rules, because it is in contrast to standard ad-hoc policy rules which contain only government debt and in line with Cúrdia and Reis (2010). The authors demonstrate that standard medium-scale DSGE models are misspecified with respect to fiscal policy. In addition, the importance of carefully modeled fiscal policy is further stressed by the historical shock decomposition of the average tax rates. Our estimated tax rules capture the cyclical behavior of fiscal policy. Therefore, we can better understand and quantify the stabilizing role of the fiscal authority and we can better distinguish between automatic stabilizing fiscal policy and exogenous tax shocks (e.g. Auerbach, 2002; Leeper et al., 2010).

This paper adds to the recent literature in various ways. One strand of the literature investigates fiscal policy from a welfare-maximizing perspective. The suggested approach is in the spirit of Benigno and Woodford (2006a) to determine the feedback variables in policy feedback rules. As shown in Benigno and Woodford (2006b), this approach delivers complex rules depending on a number of variables. Ultimately, we are interested in simple feedback rules rather than in a description of complete optimal policy (e.g. Kirsanova, Satchi, Vines, and Wren-Lewis, 2007). In particular, we select only those variables for the feedback rules which influence welfare's moments most. Furthermore, while the analytic approach postulated by Benigno and Woodford (2006a) involves very tedious algebra, it also makes it less applicable for medium-scaled DSGE models. Our approach is straightforwardly applicable to more complex DSGE models. While Benigno and Woodford (2006b) derive optimal policy rules, Schmitt-Grohé and Uribe (2004, 2006) estimate feedback parameters of simple monetary and fiscal policy rules to mimic the dynamic behavior of the welfare-optimizing Ramsey planner. Moreover, Schmitt-Grohé and Uribe (2007) determine optimal and simple feedback rules by maximizing a second-order welfare approximation of the model. The setup of our work is closely related to these latter papers, but differs in two important aspects. First and foremost, the motivation of our approach is to determine the most important feedback variables to mimic the optimal dynamic behavior of the welfare-optimizing policymaker. The final optimized simple linear rules are optimized with respect to their feedback variables rather than to their parameter loadings. Second, we use a full-fledged maximum likelihood estimation approach instead of the method of moments estimation or second-order welfare maximization when approximating the optimal policy rules with linear feedback rules. The additional information contained in the maximum likelihood approach makes it more efficient in terms of optimization and enables us to reach the position to start with a much larger and more agnostic policy rule.

Another strand of the literature has sought to empirically characterize fiscal feedback rules (e.g. Leeper et al., 2010; Forni et al., 2009). Both studies include at least debt in the fiscal feedback rules. The motivation for this is that the inter-temporal government budget constraint has to be fulfilled under all circumstances. While debt can be used to offset shocks to the economy, taxes and government spending have to adjust in the long run to ensure sustainability (McCallum, 1984; Leeper, 1991). Besides this theoretical concern, empirical findings in the literature are a further motivation (e.g. Bohn, 1998). What is more, recent empirical work has tended to focus on the short-run cyclical behavior of fiscal policy rather than on the long-run sustainability of fiscal policy (see Taylor, 2000; Auerbach, 2002; Favero and Monacelli, 2005). The intention behind this is to capture the recently increased activism of fiscal policy as mentioned by Auerbach (2002) as well as the observation that the "[...] overall size of the actual changes in taxes and spending due to the automatic stabilizers are frequently much larger than even the proposed discretionary changes. Both types of changes in taxes and spending impact aggregate demand, but the automatic ones are more predictable and work more quickly than the discretionary ones" (Taylor, 2000). Subsequently, the recent DSGE literature aims at characterizing automatic stabilizers in policy rules. For example, Jones (2002) assumes that fiscal policy responds to current and lagged output as well as hours worked and Leeper et al. (2010) include output as an additional variable in the policy rules and consider potential correlations in the tax rates. In this paper, we use a normative approach to derive simple fiscal feedback rules that characterize the fiscal policy authority operating in the model economy.

The remainder of the paper is organized as follows. Section 2 describes the model of the private sector and the monetary authority. The model is parameterized in Section 3.

In Section 4 we present the methodology to determine the policy rules. In Section 5 we investigate the empirical relevance of the policy rules and discuss the consequences. Section 6 concludes.

2 The Model

In this section, we initially set up the economy, for which we derive the fiscal policy rules. We assume that the private sector as well as the monetary authority can be described by a conventional New Keynesian DSGE model. The model includes several real frictions: internal habit formation, capital utilization, and investment adjustment costs. It also comprises two nominal rigidities for wages and prices, both following the adjustment process postulated by Calvo (1983). The fiscal policy sector is modeled following Benigno and Woodford (2006b) with wasteful government spending and distortionary taxes on capital and wages but also lump-sum taxation.

When choosing the model for the illustration of our approach to determining policy feedback rules for tax instruments, we are faced with the trade-off between the fact that the model should not be too simple in order to approximate the private sector, but that it should also be widely known and accepted as a standard and state-of-the-art model. The model presented here, as in the succession of Christiano, Eichenbaum, and Evans (2005), and Smets and Wouters (2007), meets both requirements. It is designed to capture the behavior of the private sector well and is widely acknowledged as one of the workhorses in dynamic macroeconomics. Additionally, the model contains a government sector, including feedback rules for distortionary tax rates (e.g. Benigno and Woodford, 2006b). We stick with the model since, firstly, it is close to the related literature and our results are thus more comparable and, secondly, it is a model with which researchers have recently been aiming to replicate a fiscal policy sector.

2.1 Model Description

Throughout the model description, capital letters denote nominal variables and lower-case letters real variables. An exception is investment, which is always expressed in real terms as I.

In the economy, there exists a continuum of households indexed by $i \in [0,1]$. Each household i consumes $c(i)$ and provides labor services $l(i)$. Consumers' preferences are characterized by the discount factor β, the inverse of the intertemporal substitution elasticity σ_c, and the inverse of the labor supply elasticity with respect to wages σ_l. The parameter h measures the internal habit persistence regarding consumption. Lifetime utility takes the following functional form:

$$E_t \sum_{t=1}^{\infty} \beta^t \left[\frac{\left(c_t(i) - hc_{t-1}(i)\right)^{1-\sigma_c}}{1-\sigma_c} - \frac{l_t(i)^{1+\sigma_l}}{1+\sigma_l} \right] \tag{1}$$

The intertemporal budget constraint of household i is given by:

$$\begin{aligned} c_t(i) + I_t(i) + b_t(i) = (1-\tau_t^w) \frac{W_t(i)}{P_t} l_t(i) + \left(\left(1-\tau_t^k\right) r_t^k u_t(i) - \phi_t(u(i)) \right) k_{t-1}(i) \\ + \frac{\varepsilon_{q,t-1} R_{t-1} b_{t-1}(i)}{\pi_t} + (1-\tau_t^k) d_t(i) + \iota_t(i) + \tau_t^L. \end{aligned} \tag{2}$$

Wages W are set according to a Calvo wage-setting scheme. The household invests $I(i)$ into capital k. The rental rate on capital is denoted by r^k and firms' dividends by d. The household pays lump-sum taxes (or receives transfers) τ^L as well as distortionary taxes τ^w and τ^k on labor income and capital income, respectively. Household i holds government bonds B yielding return R. Government bonds are subject to a shock ε_q that introduces a wedge between the interest rate controlled by the monetary authority and the government bonds. This risk premium shock follows the autoregressive process

$$\log \varepsilon_{q,t} = \rho_q \log \varepsilon_{q,t-1} + \epsilon_t^q, \tag{3}$$

with ϵ^q *i.i.d.* distributed.

The utilization rate of capital can be varied equivalently to the assumption made by Smets and Wouters (2007). The cost of capacity utilization is given by $\phi(\cdot)$. We assume the functional form:

$$\phi_t(u) = \frac{(1-\bar{\tau}_k)\bar{r}^k}{\sigma_u}\left(\exp\left(\sigma_u\left(u_t-1\right)\right)-1\right) \tag{4}$$

Capital depreciates at a constant rate δ. Investments are subject to a convex investment adjustment cost $s(\cdot)$

$$s_t\left(\frac{\varepsilon_{i,t}I_t}{I_{t-1}}\right) = \frac{\nu}{2}\left(\frac{\varepsilon_{i,t}I_t}{I_{t-1}}-1\right)^2, \tag{5}$$

where ε_i denotes an investment-specific efficiency shock to the adjustment costs and is supposed to follow an autoregressive process

$$\log\varepsilon_{i,t} = \rho_i\log\varepsilon_{i,t-1}+\epsilon_t^i, \tag{6}$$

with ϵ^i assumed to be *i.i.d.* distributed. Capital accumulation is described by

$$k_t(i) = (1-\delta)\,k_{t-1}(i) + \left[1-s_t\left(\frac{\varepsilon_{i,t}I_t}{I_{t-1}}\right)\right]I_t(i)\,. \tag{7}$$

To ensure homogeneity of the households with respect to consumption and asset holdings, but heterogeneity with respect to wages and hours worked in equilibrium, households receive the net cash flow from state-contingent securities ι (see e.g. Christiano et al., 2005).

Maximizing lifetime utility (1) subject to the budget constraint (2) and the capital accumulation equation (7) with respect to c, k, u, b and I yields the following first-order conditions:[2]

$$\chi_t = (c_t - hc_{t-1})^{-\sigma_c} - \beta h (c_{t+1} - hc_t)^{-\sigma_c} \tag{8}$$

$$\frac{1}{R_t^b} = \beta \frac{\chi_{t+1}\varepsilon_{q,t}}{\chi_t \pi_{t+1}^p} \tag{9}$$

$$q_t = \beta E_t \left[\frac{\chi_{t+1}}{\chi_t} \left(\psi' \left(u_{t+1} \right) u_{t+1} - \psi \left(u_{t+1} \right) + q_{t+1} \left(1 - \delta \right) \right) \right] \tag{10}$$

$$\phi_t' = r_t^k \left(1 - \tau_t^k \right) \tag{11}$$

$$q_t = \frac{1 - \beta E_t \left[\frac{\chi_{t+1}}{\chi_t} q_{t+1} s_{t+1}' \varepsilon_{i,t+1} \left(\frac{I_{t+1}}{I_t} \right)^2 \right]}{1 - s_t - s_t' \frac{\varepsilon_{i,t} I_t}{I_{t-1}}} \tag{12}$$

In the foregoing equations, χ_t denotes the marginal utility of consumption and q_t the marginal utility of capital relative to the marginal utility of consumption.

Wage setting is modeled following Erceg, Henderson, and Levin (2000), i.e. analogously to staggered price setting. Each household supplies a differentiated type of labor service, $l(i)$, which is aggregated into a homogenous labor good by a representative competitive firm (labor packer) according to a Dixit-Stiglitz aggregator with $\theta_w > 1$ denoting the elasticity of substitution

$$l_t^d = \left[\int_0^1 l_t \left(i \right)^{\frac{\theta_w - 1}{\theta_w}} \right]^{\frac{\theta_w}{\theta_w - 1}}. \tag{13}$$

Minimizing costs $W_t l_t^d$ and taking the individual wage costs of household i, $W_t(i)$, as given yields the demand for labor of type i. For any wage rate, each household supplies as many labor services as demanded.

In each period, household i is allowed to set its wage with probability $1 - \gamma_w$. Household i chooses its optimal wage $W_t^\star = W_t(i)$ by maximizing the objective function

$$\max_{W_t(i)} \quad E_t \left[\sum_{k=0}^{\infty} \left(\gamma_w \beta \right)^k \left[\chi_{t+k} W_t \left(i \right) l_{t+k} \left(i \right) - U \left(l_{t+k} \left(i \right), c_{t+k} \left(i \right) \right) \right] \right]. \tag{14}$$

If the household is not allowed to set its wage, wages are adjusted by the steady-state inflation

[2]Since the first-order conditions for household i are identical to the first-order conditions after aggregation, we report the aggregated first-order conditions for the sake of space.

rate of the economy $\bar{\pi}$:

$$W_t(i) = \bar{\pi} W_{t-1}(i). \tag{15}$$

By defining the real wage inflation π^w as

$$\pi_t^w = \frac{w_t}{w_{t-1}} \pi_t \tag{16}$$

and using the definition of labor demand for household i, we write the equation for the first-order condition to the maximization problem (14) in recursive form as:

$$K_t^w = \left(l_t^d\right)^{1+\sigma_l} + \beta \gamma_w \left(\frac{\bar{\pi}}{\pi_{t+1}^w}\right)^{-\theta_w(1+\sigma_l)} K_{t+1}^w \tag{17}$$

$$F_t^w = \frac{(\theta_w - 1)}{\theta_w} \left(1 - \tau_t^w\right) l_t^d \chi_t + \beta \gamma_w \left(\frac{\pi_{t+1}}{\pi_{t+1}^w}\right)^{-\theta_w} \left(\frac{\bar{\pi}}{\pi_{t+1}}\right)^{1-\theta_w} F_{t+1}^w \tag{18}$$

$$\frac{K_t^w}{F_t^w} = \frac{1}{\psi_l} \left(w_t^*\right)^{1+\theta_w \sigma_l} w_t \tag{19}$$

The law of motion for $w_t^* = \frac{W_t^\star}{W_t}$ is given by:

$$1 = \gamma_w \left(\frac{\bar{\pi}}{\pi_t^w}\right)^{1-\theta_w} + (1 - \gamma_w) \left(w_t^*\right)^{1-\theta_w} \tag{20}$$

The economy consists of two firm sectors. In one sector, perfectly competitive firms produce the final good y using as inputs intermediate goods $y(j)$ produced by monopolistically competitive firms indexed by j. Final-goods firms have access to the constant-returns-to-scale production function with elasticity of substitution θ_p

$$y_t = \left[\int_0^1 y_t(j)^{\frac{\theta_p - 1}{\theta_p}}\right]^{\frac{\theta_p}{\theta_p - 1}}. \tag{21}$$

Cost minimization yields the demand for each intermediate good $y(j)$ and the corresponding price index.

The intermediate goods are produced by an existing continuum of monopolistically competitive firms $j \in [0,1]$ using the production function

$$y_t(j) = (u_t k_{t-1}(j))^{\alpha} \left(l_t^d(j)\,\varepsilon_{z,t}\right)^{1-\alpha} - \Omega, \tag{22}$$

where α denotes the output elasticity with respect to capital and Ω fixed costs of production. The assumption of fixed costs is made to ensure that the production function exhibits increasing returns to scale. The variable ε_z represents a labor-augmenting productivity shock assumed to follow the process

$$\log \varepsilon_{z,t} = \rho_z \log \varepsilon_{z,t-1} + \epsilon_t^z \tag{23}$$

Intermediate-good firms maximize profits:

$$\max_{u_t \cdot k_{t-1}, l_t} \left[\left[\frac{P_t(i)}{P_t}\right]^{-\theta_p} \left(y_t(j) - w_t l_t^d(j) - r_t^k u_t k_{t-1}(j)\right)\right] \tag{24}$$

Marginal costs are denoted by z. The first-order conditions of (24) are given by:

$$z_t (1-\alpha)(u_t k_{t-1})^{\alpha} \left(l_t^d \varepsilon_{z,t}\right)^{-\alpha} = w_t \tag{25}$$

$$z_t \alpha (u_t k_{t-1})^{\alpha-1} \left(l_t^d \varepsilon_{z,t}\right)^{1-\alpha} = r_t^k \tag{26}$$

The profits of the intermediate firm are then defined as

$$d_t = y_t - r_t^k u_t k_{t-1} - w_t l_t^d. \tag{27}$$

Intermediate-good firms are subject to staggered price setting, i.e. they are allowed to adjust their prices with probability $(1-\gamma_p)$. Price-resetting firms choose $P_t^\star = P_t(j)$ to maximize the expected sum of discounted future profits:

$$\max_{P_t(j)} \quad E_t \sum_{k=0}^{\infty} \gamma_p^k m_{t+k} \left[P_t(j)\, y_{t+k}(j) - Z_{t+k} y_{t+k}(j) \;\; ,\right] \tag{28}$$

where future profits are discounted by the stochastic discount factor $m_{t+j} = \beta^j \frac{\chi_{t+j} P_t}{\chi_t P_{t+j}}$.

Prices of firms which cannot re-optimize evolve according to $P_t(i) = \bar{\pi} P_{t-1}$. Defining $p_t^* = \frac{P_t^\star}{P_t}$, using the demand for firm j and the aggregate price index, we denote the first-order condition to the maximization problem (28) and the law of motion for p_t^* as:

$$F_t^p = y_t^d \chi_t + \gamma_p \beta \left(\frac{\bar{\pi}}{\pi_{t+1}} \right)^{1-\theta_p} F_{t+1}^p \tag{29}$$

$$K_t^p = \frac{\theta_p}{\theta_p - 1} y_t^d \chi_t z_t + \gamma_p \beta \left(\frac{\bar{\pi}}{\pi_{t+1}} \right)^{-\theta_p} K_{t+1}^p \tag{30}$$

$$\frac{K_t^p}{F_t^p} = p_t^* \tag{31}$$

$$1 = \gamma_p \left(\frac{\bar{\pi}}{\pi_t} \right)^{1-\theta_p} + (1 - \gamma_p) \left(p_t^* \right)^{1-\theta_p} \tag{32}$$

The monetary authority sets nominal interest rates according to a Taylor rule that includes lagged nominal interest rates, lagged output, current inflation, and an *i.i.d.* monetary policy shock ϵ^m:

$$\log R_t = \rho_R \log R_{t-1} + (1 - \rho_R) \left(\bar{R} + \rho_\pi \left(\log \pi_t - \log \bar{\pi} \right) + \rho_y \left(\log y_{t-1} - \log \bar{y} \right) \right) + \epsilon_t^m \tag{33}$$

The fiscal authority receives tax revenues x and issues bonds b to finance government consumption expenditure c^g. The government budget constraint therefore reads as:

$$\left[\frac{b_t \pi_{t+1}}{\varepsilon_{q,t} R_t} - b_{t-1} \right] = c_t^g - x_t - \tau_t^L \tag{34}$$

Government tax revenues consist of taxes on wages and capital:

$$x_t = \tau_t^w w_t l_t + \tau_t^k \left[r_t^k u_t k_{t-1} + d_t \right] \tag{35}$$

Government consumption expenditures and lump-sum taxes evolve according to exogenous autoregressive processes

$$\log c_t^g = \rho_{cg} \log c_{t-1}^g + (1 - \rho_{cg}) \log \bar{c}^g + \epsilon_t^{cg}, \tag{36}$$

$$\log \tau_t^L = \rho_L \log \tau_{t-1}^L + (1 - \rho_L) \log \bar{\tau}^L + \epsilon_t^L, \tag{37}$$

where ϵ^{cg} and ϵ^L represent *i.i.d.* error terms.

This paper's analysis focuses on policy feedback rules for taxes on capital income and labor income. We assume the tax rates are given by policy feedback rules, which are functions of the model's variables, X_t^z, policy feedback parameters, θ^P, and corresponding $i.i.d.$ error terms, ϵ_{t,τ^w} and ϵ_{t,τ^k}:

$$\log \tau_t^w = f\left(X_t^z, \epsilon_{t,\tau^w}, \theta^P\right), \tag{38}$$

$$\log \tau_t^k = f\left(X_t^z, \epsilon_{t,\tau^k}, \theta^P\right), \tag{39}$$

The formulation of sticky prices and wages implies inefficiencies and output losses relative to an economy with flexible prices in the goods and labor market. For this reason, we have to take the effects of price and wage dispersion into account when aggregating across firms and households (e.g. Schmitt-Grohé and Uribe, 2006). Following on from Schmitt-Grohé and Uribe (2006), we use the variable p_t^+ to capture the resource costs induced by inefficient price dispersion:

$$p_t^+ = (1-\gamma_p)\left(p_t^*\right)^{-\theta_p} + \gamma_p \left(\frac{\bar{\pi}}{\pi_t}\right)^{-\theta_p} p_{t-1}^+ \tag{40}$$

The resource constraint, i.e. equilibrium condition of the goods market, is then given by

$$\frac{\left((u_t k_{t-1})^{\alpha}\left(l_t^d \varepsilon_{z,t}\right)^{1-\alpha} - \Omega\right)}{p_t^+} = c_t + I_t + c_t^g + \phi_t\left(u_t\right) k_{t-1} \tag{41}$$

To take the loss in output caused by wage dispersion into account, we use the variable w_t^+, which is defined as:

$$w_t^+ = (1-\gamma_w)\left(w_t^*\right)^{-\theta_w} + \gamma_w \left(\frac{\bar{\pi}}{\pi_t^w}\right)^{-\theta_w} w_{t-1}^+ \tag{42}$$

The equilibrium condition of the labor market then becomes:

$$l_t = w_t^+ l_t^d \tag{43}$$

The dispersion of wages causes a dispersion in utility across households. This dispersion is measured by the variable $\tilde{w}_t^+$:

$$\tilde{w}_t^+ = (1-\gamma_w)\left(w_t^*\right)^{-\theta_w(1+\sigma_l)} + \gamma_w \left(\frac{\bar{\pi}}{\pi_t^w}\right)^{-\theta_w(1+\sigma_l)} \tilde{w}_{t-1}^+ \tag{44}$$

Finally, aggregated utility across households is:

$$U_t = \frac{(c_t - hc_{t-1})^{1-\sigma_c}}{1-\sigma_c} - \frac{\tilde{w}_t^+ \left(\frac{l_t}{w_t^+}\right)^{1+\sigma_l}}{1+\sigma_l} \tag{45}$$

The competitive equilibrium can now be defined as follows: A stationary competitive equilibrium is a set of stationary processes F_t^w, F_t^p, K_t^w, K_t^p, p_t^*, w_t^*, d_t, p_t^+, w_t^+, $\tilde{w}_t^+$, π_t^w, π_t, w_t, y_t, l_t, k_t, z_t, $\varepsilon_{i,t}$, $\varepsilon_{z,t}$, $\varepsilon_{q,t}$, s_t, ϕ_t, χ_t, I_t, c_t, u_t, r_t^k, l_t^d, b_t, x_t, R_t, τ_t^w, τ_t^k, τ_t^L, c_t^g satisfying equations (3) - (7), (8) - (12), (16) - (20), (23), (25) - (27), (29) - (43), given exogenous stochastic processes $\{\epsilon_t^i, \epsilon_t^q, \epsilon_t^z, \epsilon_t^{cg}, \epsilon_{t,\tau^k}, \epsilon_{t,\tau^w}, \epsilon_t^L, \epsilon_t^m, \}_{t=0}^{\infty}$, and the initial conditions $\varepsilon_{i,0}$, $\varepsilon_{z,0}$, $\varepsilon_{q,0}$, c_0^g, τ_0^L, τ_0^w, τ_0^k, R_{-1}, c_{-1}, I_{-1}, k_{-1}, p_{-1}^+, w_{-1}, w_{-1}^+,$\tilde{w}_{-1}^+$, b_{-1}.

In the next section we are going to parameterize the model.

3 Parametrization of the Model

To parameterize the private sector behavior and the monetary authority we estimate the model using Bayesian estimation methods.

3.1 Data

As observable variables we employ private consumption, private investment, output, inflation, tax rates on capital and wages, public transfers, interest rates, and tax revenues. Since the model is not thought of as giving a precise description of tax revenues, we add a measurement error to the tax revenue observation equation. This leaves us with eight structural shocks incorporated in the model, and one measurement error, which correspond to the nine observable variables.

The time series are quarterly US data. A detailed description of the source can be found in appendix A. The tax rates are computed as in Jones (2002). Whenever necessary, the data are transformed into real terms and per capita.

Since the employed model does not exhibit an endogenous trend, we de-trend the data prior to the estimation. In contrast to most studies in the literature, we do not use a first-difference filter to de-trend the data, because it puts too much weight on high frequencies of the data. Instead, we employ a one-sided HP filter.[3] In contrast to the two-sided HP filter, the one-sided HP filter is not adversely affected by the correlation of data points with subsequent observations. The one-sided HP filter is implemented for each time series using an initialization window of 40 quarters.

The complete data set ranges from 1958:1 to 2009:2. For the estimation procedure we employ only a sub-sample covering 1983:1 to 2008:4. We choose this particular sample for two reasons: first, to exclude the high-inflation period during the 1970s and the Volcker disinflation years, and second, because monetary policy is characterized by a Taylor rule (Taylor, 1993) and thought to be active, whereas fiscal policy is assumed to be passive (in the spirit of Leeper, 1991). All of these assumptions are included in our model setup and by the subsequent prior choice.

3.2 Prior Choice and Calibrated Parameters

We calibrate the discount factor $\beta = 0.9926$ to yield a steady-state quarterly real interest rate of 1.25%. In order to match an investment-to-output ratio of 11.43% after taxes, we set the share of capital in production to $\alpha = 0.3$ and the depreciation rate of capital to $\delta = 0.025$. Similarly to Schmitt-Grohé and Uribe (2004), the elasticities of substitution between intermediate goods θ_p and labor inputs θ_w are chosen so that the steady-state mark-up for prices and wages is 20% and 10%, respectively.

The steady-state ratio of government consumption expenditures to output $\bar{c}^g/\bar{y}$ and the steady-state ratio of lump-sum taxes to output $\bar{\tau}^L/\bar{y}$ is set to 18% and -7%, respectively. This implies a ratio of private consumption to output $\bar{c}/\bar{y}$ of approximately 60%. The steady-state value of annual inflation is calibrated as $\bar{\pi} = 1.0112$; the steady-state values for the tax rates on capital $\bar{\tau}^k = 0.3572$ and wages $\bar{\tau}^w = 0.2343$ are the averages of our time series.

[3] The filter is parameterized with $\lambda_{HP} = 1600$.

The remaining parameters are estimated. In general, we follow the most recent and widely accepted studies for our choice of the prior distributions (see e.g. Smets and Wouters, 2007; Christiano, Motto, and Rostagno, 2010). In some cases, we deviate from that literature to allow for a slightly wider and less informative prior distribution.

More precisely, we choose a Gamma distribution with a standard deviation of 0.5 and a mean of 1.5 and 2 for the inverse intertemporal elasticity of substitution and the inverse Frisch elasticity, respectively. These values are in line with Smets and Wouters (2007). The habit parameter is assumed to be Beta-distributed with mean 0.5 and a standard deviation of 0.15. For the investment adjustment cost parameter we specify a Gamma distribution with mean 4 and standard distribution 1.25.

The utilization costs are characterized by σ_u, which is estimated by Altig, Christiano, Eichenbaum, and Lindé (2010) to be 2.02. We therefore define a Gamma distribution centered around 2 with standard deviation 0.5. The Calvo probabilities for price and wage contracts are assumed to be Beta-distributed with mean 0.5 and a standard deviation of 0.15, implying an average duration of price and wage contracts of two quarters.

In order to parameterize the private sector we have to specify the fiscal policy in more detail to close the model. For this reason we choose simple fiscal feedback rules(see e.g. Forni et al., 2009):

$$\log \tau_t^w = (1-\rho_w)\left(\log \bar{\tau}^w - \eta_w \log \bar{b}\right) + \rho_w \log \tau_{t-1}^w + (1-\rho_w)\,\eta_w \log b_{t-1} + \epsilon_{t,\tau^w}, \tag{46}$$

$$\log \tau_t^k = (1-\rho_k)\left(\log \bar{\tau}^k - \eta_k \log \bar{b}\right) + \rho_k \log \tau_{t-1}^k + (1-\rho_k)\,\eta_k \log b_{t-1} + \epsilon_{t,\tau^k}, \tag{47}$$

where ϵ_{t,τ^w} and ϵ_{t,τ^k} denote *i.i.d.* error terms.

Since we employ the same fiscal policy rules as Forni et al. (2009), we also choose similar prior distributions for the parameters: The autoregressive coefficients are assumed to be Beta-distributed with mean 0.85 and a standard deviation of 0.1, and the coefficients on government debt are Gamma-distributed with mean 0.4 and a standard deviation of 0.2.

Concerning the monetary policy rule, we follow Christiano et al. (2010) in choosing a Beta distribution with mean 0.8 and a standard deviation of 0.1 for the interest rate smoothing coefficient, a Gamma distribution with mean 1.7 and standard deviation 0.1 for the policy coefficient on inflation, and a Normal distribution with mean 0.125 and standard deviation 0.05 for the policy coefficient on output. For the AR(1) coefficients of the shock processes we choose Beta distributions with mean 0.85 and standard deviation 0.1. The standard deviations of the structural shocks are assumed to be Inverse-Gamma distributed with mean 0.01 and 4 degrees of freedom.

3.3 Estimation Results

In this section, we present our estimation results. The estimation results of the private sector's structural parameters and the monetary authority are essential to the following analysis. Therefore, we focus on discussing their estimates and juxtaposing them to the relevant study by Smets and Wouters (2007).

First, we estimate the posterior mode of the distribution and employ a random walk Metropolis-Hastings algorithm to approximate the distribution around the posterior mode. We run two chains, each with 1,000,000 parameter vector draws. The first 90% have been discarded.[4]

The plot indicates that the posterior distributions of all structural parameters are well approximated around the posterior mode. It also implies that all parameters, except the inverse of the Frisch elasticity, σ_l, are identified as being substantially different from their prior distribution.[5] Table 1 provides detailed posterior statistics, e.g. posterior mean and the HPD interval of 10% and 90%. The posterior distributions of the parameters are similar to those obtained by Smets and Wouters (2007). In the following paragraphs we focus on comparing our parameter estimates to theirs.

The parameter estimates associated with the households' preferences are very much in line

[4] Convergence statistics and further diagnostics are provided in the technical appendix on our websites, e.g. *http://www.mwpweb.eu/AlexanderKriwoluzky/research_current_projects.html*.

[5] The difficulty in identifying the inverse of the Frisch elasticity, σ_l, stems from our choice of the observable variables, which leads to a rather flat likelihood as indicated by the check plots in the technical appendix.

Parameter	Symbol	Mode	Mean	10%	90%
Inv. intertemp. subst. elasticity	σ_c	1.5932	1.6419	1.0484	2.2102
Inverse Frisch elasticity	σ_l	1.8663	1.9522	1.1264	2.7671
Habit persistence	h	0.4791	0.4867	0.3717	0.5978
Price stickiness	γ_p	0.5764	0.5868	0.5006	0.6778
Wage stickiness	γ_w	0.6268	0.6202	0.5178	0.7292
Investment adjustment cost	ν	4.4756	5.0134	3.0526	6.8946
Capital utilization cost	σ_u	2.6778	2.7955	2.0049	3.6010
Interest rate AR coefficient	ρ_R	0.7991	0.7997	0.7594	0.8397
Inflation coefficient	ρ_π	1.7737	1.7799	1.6174	1.9354
Output coefficient	ρ_y	0.0809	0.0858	0.0423	0.1295
Labor tax AR coefficient	ρ_w	0.8501	0.8500	0.7656	0.9371
Labor tax debt coefficient	η_{wb}	0.2770	0.3764	0.1471	0.6097
Capital tax AR coefficient	ρ_k	0.8425	0.8437	0.7687	0.9212
Capital tax debt coefficient	η_{kb}	0.2414	0.3340	0.0912	0.5735
Lump-sum tax AR coefficient	ρ_{τ^l}	0.7592	0.7582	0.6574	0.8583
Adjustment costs AR coefficient	ρ_i	0.4821	0.4950	0.3620	0.6246
Technology AR coefficient	ρ_z	0.9545	0.9320	0.8817	0.9881
Risk premium AR coefficient	ρ_q	0.8330	0.8172	0.7429	0.8928
Public consumption AR coefficient	ρ_{cg}	0.7838	0.7857	0.6877	0.8859
S.d. adjustment costs shock	ϵ_i	0.0279	0.0288	0.0244	0.0334
S.d. technology shock	ϵ_z	0.0057	0.0063	0.0047	0.0078
S.d. risk premium shock	ϵ_q	0.0038	0.0044	0.0026	0.0061
S.d. monetary policy shock	ϵ_m	0.0015	0.0016	0.0014	0.0018
S.d. labor tax shock	ϵ_{τ^w}	0.0216	0.0220	0.0194	0.0246
S.d. capital tax shock	ϵ_{τ^k}	0.0241	0.0244	0.0215	0.0271
S.d. lump-sum tax shock	ϵ_{τ^l}	0.0238	0.0242	0.0213	0.0269
S.d. public consumption shock	ϵ_{cg}	0.0156	0.0159	0.0141	0.0178
S.d. measurement error taxes	ϵ_{tax}	0.0100	0.0101	0.0090	0.0113
Log data density		3131.84	3132.25		

Table 1: Posterior mode and posterior distribution of the benchmark model's parameters.

with the literature. The estimate of the inverse elasticity of the intertemporal substitution, $\sigma_c = 1.59$, and the estimate of the inverse of the Frisch elasticity, $\sigma_l = 1.86$, are close to those obtained by Smets and Wouters (2007), $\sigma_c = 1.39$, $\sigma_l = 1.92$. The posterior mode of the habit parameter, $h = 0.48$, is lower than the estimate by Smets and Wouters (2007), 0.71, but higher than the estimate by Levin, Onatski, Williams, and Williams (2005), 0.29. While the capacity utilization cost $\sigma_u = 2.68$ is found to be higher than the value proposed by Altig et al. (2010), $\sigma_u = 2.02$, the estimate describing the investment adjustment cost $\nu = 4.48$ is lower than the value found by Smets and Wouters (2007), $\nu = 5.48$.

The estimates of the monetary policy rule are close to other studies in the literature: the interest rate-smoothing coefficient $\rho_r = 0.80$, the inflation coefficient $\rho_\pi = 1.77$ and the coefficient on output $\rho_y = 0.08$ are found, inter alia, by Smets and Wouters (2007).

The Calvo parameters of wage stickiness and price stickiness are estimated at $\gamma_w = 0.63$ and $\gamma_p = 0.58$, respectively. Both estimates are lower than the estimates of Smets and Wouters (2007), who estimate $\gamma_w = 0.73$ and $\gamma_p = 0.65$. Our estimates imply an average duration of wage and price contracts of approximately three and two quarters, respectively. The AR(1) coefficients of the shock processes are well identified, like the standard deviations of the shock processes.

Summarizing this subsection, we find that our estimation results are well identified and sufficiently close to other studies and therefore represent a good description of the private sector of the economy and a good starting point for the subsequent identification of fiscal policy rules.

4 Determination of Fiscal Policy Rules

We are interested in the feedback variables of simple rules that have the strongest impact on the variable that is of interest to the policymaker, i.e. welfare, at the optimal allocation. In that respect, we compute the optimal allocation given the posterior estimates of the model's private sector. Section 4.2 summarizes the approximation of the optimal policy problem's highly non-linear solution with simple and linear rules. In Section 4.3, we describe the calculation of the elasticities of the moments of welfare with respect to the feedback coefficients and select the extended rules.

4.1 Optimal Policy

Given the structural estimates, we compute the optimal equilibrium of the economy described in Section 2.1. We assume that the government has operated for an infinite number of periods and honors the commitments it has made in the past. This kind of policy under commitment is optimal from a timeless perspective (Woodford, 2003). The benevolent policymaker has two instruments, taxes on labor income and taxes on capital income.

Let N be the number of endogenous variables.[6] The optimal policy problem is defined as maximizing the lifetime expected utility

$$E_0 \sum_{t=0}^{\infty} \beta^t U\left(c_t - hc_{t-1}, l_t\right), \tag{48}$$

where aggregate utility is defined by eq. (45), subject to the following $(N-2)$ equations (4), (5), (7), (8) - (12), (16) - (20), (25) - (27), (29) - (35), and (40)- (44).

The first-order conditions of the maximization problem yield $2N-2$ equations for the N endogenous variables and $N-2$ Lagrangian multipliers associated with the private sector equilibrium constraints. The optimal equilibrium is then defined as a set of stationary variables F_t^w, F_t^p, K_t^w, K_t^p, p_t^*, w_t^*, d_t, p_t^+, w_t^+, π_t^w, π_t, w_t, y_t, l_t, k_t, z_t, $\varepsilon_{i,t}$, $\varepsilon_{z,t}$, $\varepsilon_{q,t}$, s_t, ϕ_t, χ_t, I_t, c_t, u_t, r_t^k, l_t^d, b_t, t_t, R_t, τ_t^L, τ_t^w, τ_t^k, c_t^g, $\tilde{w}_t^+$, and $N-2$ Lagrangian multipliers satisfying the first-order conditions of the optimal policy problem, as well as (3), (23), (6), (36), (37), given exogenous stochastic processes $\{\epsilon_t^i, \epsilon_t^q, \epsilon_t^z, \epsilon_t^{cg}, \epsilon_t^L, \epsilon_t^m\}_{t=0}^{\infty}$, values of the N endogenous variables dated $t < 0$, and values of the $(N-2)$ Lagrangian multipliers dated $t < 0$.

When we compute the optimal policy, we solve for steady-state values of τ^k and τ^w, which solve the first-order conditions of the policymaker's maximization problem. The steady-states of the tax rates are $\bar{\tau}_k = -0.1259$ and $\bar{\tau}_w = 0.4281$. These numbers are in line with the values computed by Schmitt-Grohé and Uribe (2006). As in their approach, the social planner faces

[6] In our benchmark model the number of endogenous variables is $N = 30$.

the following trade-off when setting the optimal tax rate for capital income and profits. On the one hand, she aims at eliminating the distortion between private and social returns on capital stemming from the price mark-up with a negative tax rate (see Judd, 2002). On the other hand, the social planner has an incentive to tax the profits with a high income tax. In the present model, the two opposite effects lead to a negative tax rate on capital and profits. To finance this subsidy and the given level of government consumption expenditures and transfers, the policymaker has to increase the tax rate on labor income.

The dynamic characteristics of the equilibrium, i.e. the impulse-response functions of some of the endogenous variables to exogenous shocks, are plotted as dashed lines in Figures 1 - 2. In general, the policymaker follows some particular principles when responding to an exogenous disturbance: offsetting efficiency losses in the short-run and financing the changes in the policy instrument, i.e. balancing the budget. This is nicely illustrated by the dynamic responses to an investment-specific shock (Figure 2). Investment drops and the tax on capital income is lowered.[7] The lower capital taxes are financed by an increase in taxes on wages. It is worth noting that, in response to a technology shock (Figure 1), both tax rates respond pro-cyclically, i.e. they increase. Fiscal policy is thus conducted counter-cyclically. A closer look at the impulse-response functions clearly shows that an increase in investment is generally accompanied by an increase in the capital income tax rate. For taxes on labor income, it seems that the responses of the real wage and hours worked determine the response of labor taxes. From this eyeball exercise, paired with some economic intuition, we expect that the coefficients on investment and hours worked or rather real wages should play an important role in approximating the optimal-policy dynamics using linear feedback rules.

To summarize, the computed optimal steady-state values for the tax on capital income and on labor income are in line with the literature. The dynamics around this steady state are also in line with our expectations about optimal fiscal policy.

[7] It should be borne in mind that the tax rate on capital income is negative in the steady state. An increase in the tax rate thus reduces subsidies.

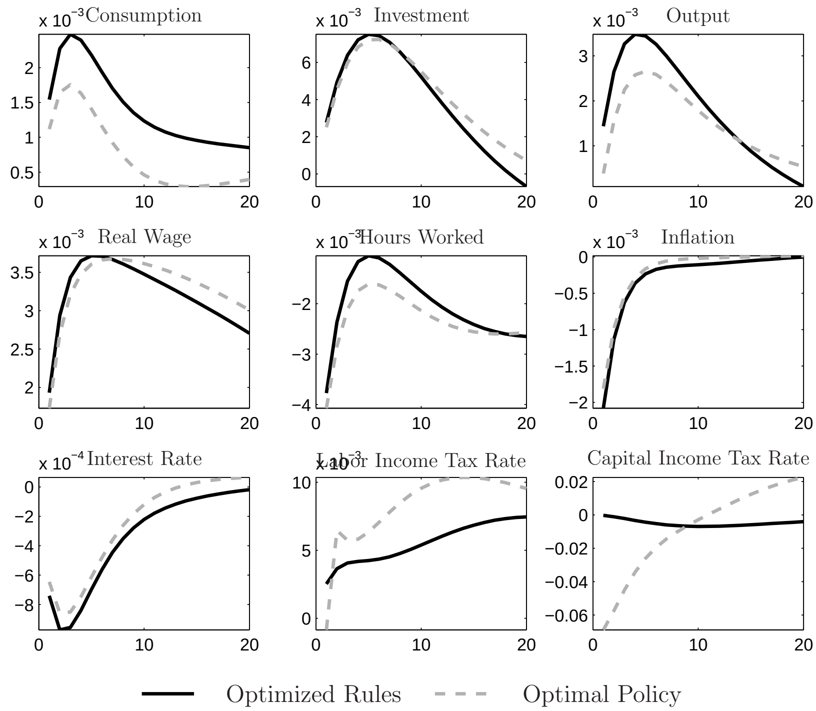


Figure 1: Impulse responses under optimized rules (solid) and optimal policy (dashed). Technology shock.

4.2 Approximation of Optimal Policy Rules by Linear Rules

In this section we describe the construction of the simple and linear rules for an approximation of the optimal policy.

Denote the set of variables the policymaker is interested in, or observable variables, by X^o. The observable variables are linked to the endogenous state variables X^z via the observation equation

$$X_t^o = HX_t^z. \tag{49}$$

The state variables evolve according to the state equation, which is the log-linearized solution of the model described in Section 2.1

$$X_t^z = T(\theta^M)X_{t-1}^z + R(\theta^M)X_t^\epsilon, \tag{50}$$

where θ^M is a vector collecting the structural parameters of the model and X^ϵ the exogenous variables. We partition the vector into two sub-vectors: $\theta^M = [\theta^S \theta^P]$. The vector θ^S contains

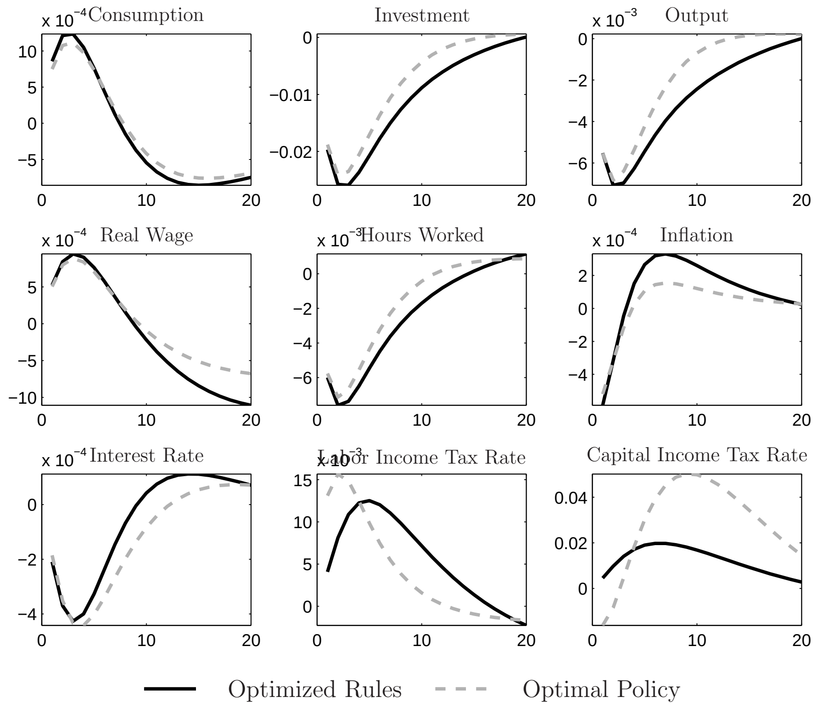


Figure 2: Impulse responses under optimized rules (solid) and optimal policy (dashed). Investment-specific shock.

all the structural model parameters which are not included in the fiscal policy rules. The coefficients of the fiscal policy rules are included in the vector θ^P. In the benchmark model, the policy rules have been assumed to be eq. (38) and (39). Here, we define two very extensive rules, including a large variety of macroeconomic variables:

$$\tau_t^w = f\left(\tau_{t-1}^w, b_{t-1}, k_{t-1}, y_t, c_t, l_t, w_t, I_t, \pi_t, R_t\right) \text{ and} \tag{51}$$

$$\tau_t^k = f\left(\tau_{t-1}^k, b_{t-1}, k_{t-1}, y_t, c_t, l_t, w_t, I_t, \pi_t, R_t\right) \tag{52}$$

The vector of corresponding policy coefficients is

$$\theta^P = [\rho_w, \eta_{wk}, \eta_{wb}, \eta_{wy}, \eta_{wc}, \eta_{wl}, \eta_{wI}, \eta_{w\pi}, \eta_{ww}, \eta_{wR}, \tag{53}$$
$$\rho_k, \eta_{kk}, \eta_{kb}, \eta_{ky}, \eta_{kc}, \eta_{kl}, \eta_{kI}, \eta_{k\pi}, \eta_{kw}, \eta_{kR}],$$

where the two subscripts denote the tax instrument and their partial elasticities with respect to the feedback variables, respectively. To estimate θ^P, we fix θ^S at its posterior mode (see

Section 3.3). Given the optimal allocation derived in Section 4.1, we simulate artificial time series. More precisely, we simulate data for output, private consumption, private investment, hours worked, and interest rates given a sequence of disturbances (ϵ_i, ϵ_z, ϵ_m, ϵ_q, ϵ_{cg}). The choice of the variables and shocks was motivated by the following considerations. The transfer shock, which is not included in the simulation, accounts for less than one percent of the variation in any of the variables in the subsequent analysis. Moreover, the choice of the variables is partly motivated by the remaining shocks in the model. The variables are also chosen because they constitute good indicators of the dynamic economic behavior. Moreover, we assume that if we are able to describe their dynamics we are also in a position to describe the dynamics of the remaining variables in the DSGE model.

We use this time series to estimate the state system consisting of (50) and (49) using Bayesian model estimation. For all feedback coefficients except for the coefficients on debt we define diffuse prior distributions, namely a Normal distribution with mean zero and a standard deviation of 0.5. In order to insure sustainability of the system, the prior distribution for the coefficient on debt is centered around 0.2 for the labor income tax rate and around -0.2 for the capital income tax rate. The negative number was chosen, because of the negative steady-state.

In order to check whether the simple linear rules are indeed a good approximation of the optimal policy rules, we plot corresponding impulse-response functions as solid lines in Figures 1 - 2. The plots indicate that the simple rules approximate the optimal policy rules satisfactorily and justify our choice of variables ex post. In the next step, the estimated posterior distributions of the feedback parameters are employed to determine those feedback coefficients that have the most impact on welfare.

4.3 Computation of the Elasticities

We calculate the elasticities of the variance of welfare with respect to the feedback coefficients employing the methodology proposed by Iskrev (2010). The methodology and our application are briefly summarized in this section.

The second moments[8] m of a set of observable variables X^o are the variance-covariance matrix $\Sigma_{m,0}$ and l autocovariances $(\Sigma_{m,1}, \ldots \Sigma_{m,l})$, which can be summarized in the vector $\Sigma_{m,L}$:

$$\Sigma_{m,L} = [vech(\Sigma_{m,0})', vec(\Sigma_{m,1})' \ldots vec(\Sigma_{m,l})']'. \tag{54}$$

The moments $\Sigma_{m,L}$ are calculated from the state space system defined by equations (50) and (49). The matrices T and R contain non-linear combinations, ς, of the structural parameter vector θ^M. In order to take into account the dependence of the moments $(\Sigma_{m,L})$ on the recursive law of motion (ς), which itself depends on structural parameters (θ^M), the Jacobian $J(L)$ is decomposed into two Jacobians

$$J(L) = J_1 J_2, \tag{55}$$

where J_1 contains the partial derivatives of the moments $\Sigma_{m,L}$ with respect to each recursive law of motion, and J_2 the partial derivatives of each recursive law of motion with respect to each parameter. Since we fix θ^S, we compute partial derivatives with respect to the 20 policy coefficients in θ^P only. We set $L = 0$, i.e. we consider the variance of welfare only[9] and use DYNARE to compute the Jacobian $J(L)$. Afterwards, we multiply the partial derivatives by the policy coefficients and divide them by the corresponding moment to calculate the elasticities. To quantify the uncertainty, we take 500 draws from the distribution of the policy coefficients derived in Section 4.2.

Table 2 presents the results. Moreover, the results are illustrated in Figure 3. The plots show the box plot of the 75% quantile with respect to each policy coefficient.

Inspecting the table and the plots, interestingly, the coefficients on the nominal interest rate and inflation are negligible for welfare's moments. The remaining feedback coefficients

[8]While the methodology proposed in Iskrev (2010) also includes first moments of the data, we only consider second moments in our estimation. The steady state of the model simulating the data and the estimated model are identical.

[9]We choose only the variance since this is the measure typically employed in the literature. The inclusion of auto-covariances is straightforward.

Feedback Parameter	Symbol	Percentile		
		50%	25%	75%
Tax Rate on Labor Income				
Labor tax rate	ρ_w	0.2717	0.1099	0.8345
Capital	η_{wk}	0.0419	0.0109	0.1681
Debt	η_{wb}	0.3148	0.1424	0.8281
Output	η_{wy}	0.0603	0.0122	0.2458
Consumption	η_{wc}	0.0969	0.0291	0.3387
Hours worked	η_{wh}	0.3069	0.1304	0.9330
Wage rate	η_{ww}	0.0859	0.0318	0.4151
Investment	η_{wI}	0.1157	0.0500	0.3172
Inflation	$\eta_{w\pi}$	0.0030	0.0008	0.0104
Nominal interest rate	η_{wR}	0.0048	0.0019	0.0109
Tax Rate on Capital Income				
Capital tax rate	ρ_k	0.1101	0.0468	0.2900
Capital	η_{kk}	0.0146	0.0056	0.0340
Debt	η_{kb}	0.1001	0.0305	0.3251
Output	η_{ky}	0.0048	0.0014	0.0124
Consumption	η_{kc}	0.0047	0.0015	0.0121
Hours worked	η_{kh}	0.0132	0.0049	0.0257
Wage rate	η_{kw}	0.0122	0.0041	0.0250
Investment	η_{kI}	0.0461	0.0230	0.1002
Inflation	$\eta_{k\pi}$	0.0004	0.0001	0.0011
Nominal interest rate	η_{kR}	0.0003	0.0001	0.0011

Table 2: Elasticity of welfare's moments w.r.t. feedback parameters of the tax rules.

have a higher impact and contribute significantly to the elasticities of welfare's variance. This result is in line with Benigno and Woodford (2006a), who find that optimal rules for taxes on capital income and labor income should respond to manifold feedback variables in their model. The motivation of the present paper is to form simple rules rather than to describe optimal policy. We therefore rank the elasticities of the feedback coefficients for every draw from the distribution of policy coefficients on an ordinal scale from 1 to 10, with 10 corresponding to the coefficient with the highest elasticity. The results are plotted in Figure 4, displaying the box plot of the 75% quantile with respect to each policy coefficient.

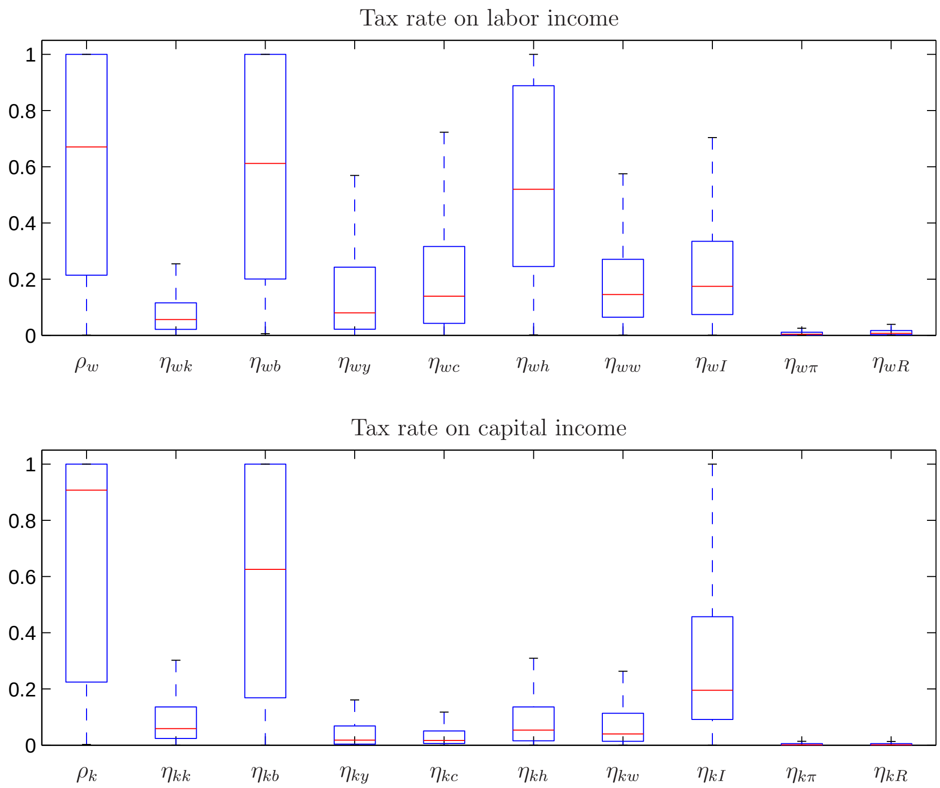


Figure 3: Relative elasticity of welfare's variance w.r.t. feedback parameters of the tax rules.

As a general rule for subsequent applications we suggest to employ the feedback variables in the feedback rules, which can be clearly distinguished from other coefficients. In our example these feedback coefficients are in each rule the autoregressive coefficient and the coefficient on government debt. Next to those coefficients, the coefficient on investment η_{kI} for the capital income tax rate as well as the coefficient on hours worked, η_{wh} for the labor income tax rate are important.

In summary, the fiscal rules are specified as:

$$\hat{\tau}_t^w = \rho_w \hat{\tau}_{t-1}^w + (1-\rho_w)\left(\eta_{wb}\hat{b}_{t-1} + \eta_{wh}\hat{l}_t\right) + \epsilon_{t,\tau^w} \tag{56}$$

$$\hat{\tau}_t^k = \rho_k \hat{\tau}_{t-1}^k + (1-\rho_k)\left(\eta_{kb}\hat{b}_{t-1} + \eta_{kI}\hat{i}_t\right) + \epsilon_{t,\tau^k} \tag{57}$$

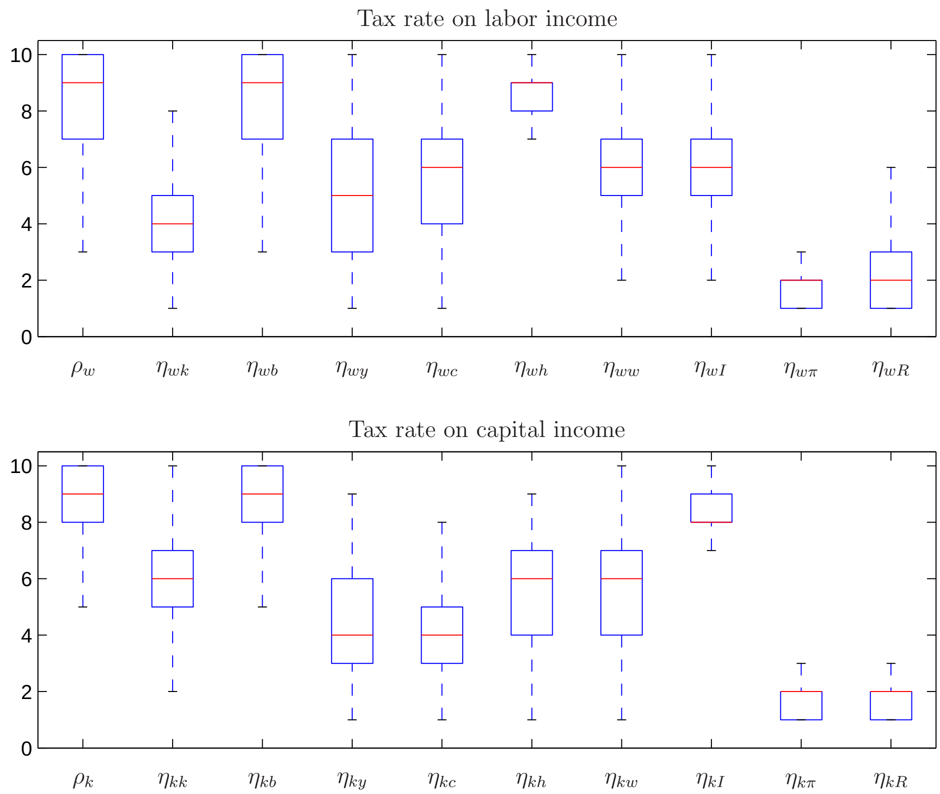


Figure 4: Importance w.r.t. feedback parameters of the tax rules.

5 Empirical Evidence

After deriving the feedback rules, we estimate the model employing the tax rules (57) and (56) instead of the rules (39) and (38). This allows us to check for the policy invariance of the private sector estimates and to verify the empirical relevance of the feedback variables.

5.1 The Estimated Fiscal Policy Rules

The model is estimated given the data, the calibration, and the prior distribution presented in the subsections 3.1 and 3.2. The prior distribution of the smoothing parameter in the equations (56) and (57) is again specified as a Beta distribution with mean 0.85 and standard deviation 0.1. Similarly, the prior distribution for the coefficients on debt is a Gamma distribution with mean 0.4 and a standard deviation of 0.2. For the remaining policy coefficients, we specify a prior which is normally distributed with mean 0 and standard deviation 0.5.

The model is estimated by running two random walk Metropolis-Hastings chains, each with 1,000,000 parameter vector draws. The first 90% are discarded. An overview of the posterior estimates is given in Table 3. Prior and posterior distributions are illustrated in Figure 5.

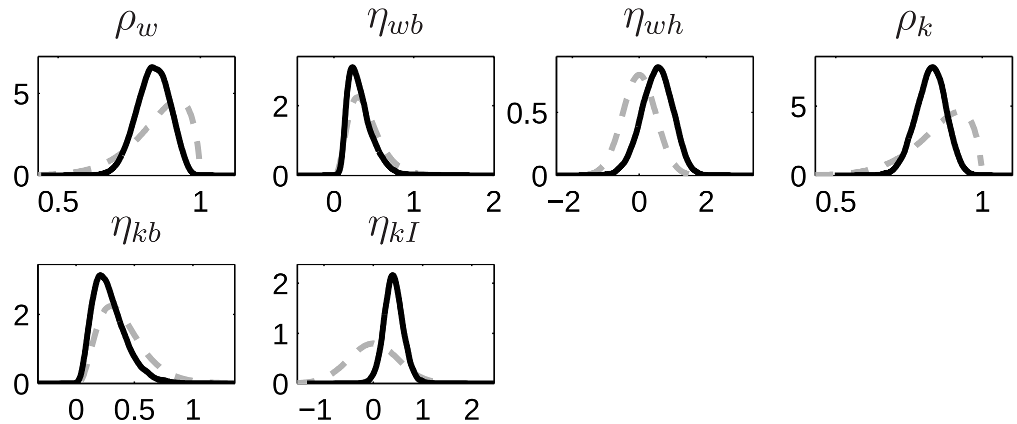


Figure 5: Prior (grey dashed) and posterior (black solid) distribution of policy feedback parameters.

The posterior distributions of the structural parameters are, although not entirely identical, not much different to those presented in Section 3.3. Similarly to the estimation results in Section 3.3, all posterior distributions of the parameters are different to the prior distribution, with the exception of the inverse of the Frisch elasticity σ_l.

The posterior modes of the parameters characterizing the preferences of the household are found to differ marginally: [10] $\sigma_c = 1.56 < 1.59$, $\sigma_l = 1.78 < 1.86$, and $h = 0.49 > 0.48$. While the parameters characterizing price stickiness, $\gamma_p = 0.58$, and investment adjustment costs, $\nu = 4.40 < 4.47$, are estimated similarly, the wage stickiness parameter is estimated to be higher, at $\gamma_w = 0.65 > 0.63$, and the capacity utilization costs at $\sigma_u = 2.63 < 2.68$.

The AR(1) coefficients of the shock processes and the standard deviation are estimated similarly too. Notable exceptions are the smaller standard deviations of the tax shocks. This follows directly from the larger systematic and endogenous tax rules employed in the

[10] The following comparisons first report the estimate of the economy with the elaborate tax rules and then relate it to the former estimate of the model.

Parameter	Symbol	Mode	Mean	10%	90%
Inv. intertemp. subst. elasticity	σ_c	1.5607	1.6369	1.0396	2.2375
Inverse Frisch elasticity	σ_l	1.7760	1.9094	1.1084	2.6405
Habit persistence	h	0.4937	0.4953	0.3822	0.6129
Price stickiness	γ_p	0.5814	0.5928	0.5050	0.6783
Wage stickiness	γ_w	0.6535	0.6399	0.5289	0.7512
Investment adjustment cost	ν	4.4001	4.8433	2.9195	6.6910
Capital utilization cost	σ_u	2.6315	2.7563	1.9525	3.5740
Interest rate AR coefficient	ρ_R	0.8005	0.8005	0.7596	0.8421
Inflation coefficient	ρ_π	1.7678	1.7804	1.6224	1.9337
Output coefficient	ρ_y	0.0815	0.0854	0.0420	0.1294
Labor tax AR coefficient	ρ_w	0.8168	0.8324	0.7417	0.9284
Labor tax debt coefficient	η_{wb}	0.2237	0.3338	0.1153	0.5666
Labor tax labor coefficient	η_{wh}	0.6178	0.5241	-0.2149	1.3025
Capital tax AR coefficient	ρ_k	0.8053	0.8237	0.7407	0.9069
Capital tax debt coefficient	η_{kb}	0.2003	0.2886	0.0716	0.5000
Capital tax investment coefficient	η_{kI}	0.4189	0.4106	0.0932	0.7255
Lump-sum tax AR coefficient	ρ_{τ^l}	0.7591	0.7586	0.6590	0.8620
Adjustment costs AR coefficient	ρ_i	0.4830	0.4966	0.3709	0.6270
Technology AR coefficient	ρ_z	0.9520	0.9332	0.8826	0.9872
Risk premium AR coefficient	ρ_q	0.8433	0.8292	0.7570	0.9007
Public consumption AR coefficient	ρ_{cg}	0.7809	0.7857	0.6873	0.8803
S.d. adjustment costs shock	ϵ_i	0.0287	0.0297	0.0248	0.0345
S.d. technology shock	ϵ_z	0.0058	0.0064	0.0048	0.0080
S.d. risk premium shock	ϵ_q	0.0037	0.0042	0.0025	0.0059
S.d. monetary policy shock	ϵ_m	0.0015	0.0016	0.0014	0.0018
S.d. labor tax shock	ϵ_{τ^w}	0.0212	0.0217	0.0192	0.0242
S.d. capital tax shock	ϵ_{τ^k}	0.0234	0.0239	0.0212	0.0266
S.d. lump-sum tax shock	ϵ_{τ^l}	0.0238	0.0241	0.0214	0.0268
S.d. public consumption shock	ϵ_{cg}	0.0147	0.0150	0.0133	0.0168
S.d. measurement error taxes	ϵ_{tax}	0.0099	0.0101	0.0089	0.0112
Log data density		3134.74	3135.30		

Table 3: Posterior distribution of the extended model's parameters.

estimation. Given these results, we can conclude that the private sector estimates are policy-invariant.

With respect to our estimated policy rules, we find that all feedback parameters are identified and different from zero. Both auto-regressive coefficients are estimated to be smaller: $\rho_k = 0.81 < 0.84$ and $\rho_w = 0.82 < 0.85$. The feedback coefficients on debt are also slightly smaller: $\eta_{wb} = 0.22 < 0.28$ and $\eta_{kb} = 0.2 < 0.24$. Thus, the relatively higher estimates are biased due to misspecified fiscal policy. The additional feedback coefficients are $\eta_{kI} = 0.42$ and $\eta_{wh} = 0.62$, the feedback coefficient of capital income taxes on investment and the feedback coefficient of labor income taxes with respect to hours worked, respectively.

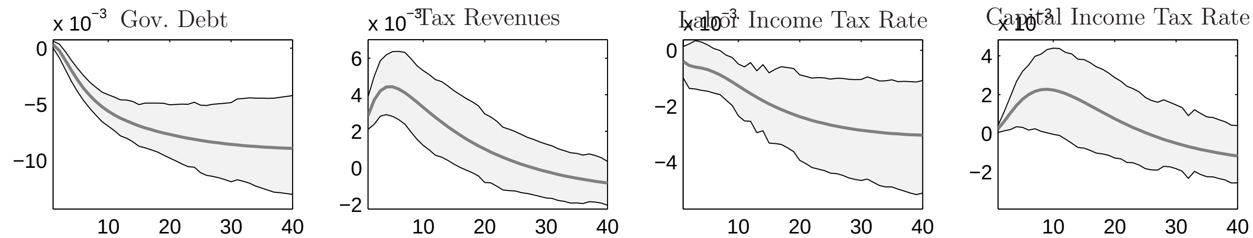
The log marginal data density is in favor of the economy with the tax rules derived in Section 4 ($3134.74 > 3132.25$). We conclude that the introduction of our feedback variables is empirically validated and that they reduce the non-systematic explanation for the fiscal policy sector. The difference in the log marginal data densities is small. This circumstance is related to the similar parameter estimates of the private sector. The dynamic behavior of the private sector variables such as output, consumption, investment, hours worked, and also nominal interest rate and inflation is just slightly different for the different policy rules too.

The main new feature is the qualitatively different characterization of the dynamic behavior of fiscal policy due to the feedback coefficients η_{kI} and η_{wh}. Next, we investigate the effects of the different policy rule in two dimensions. We analyze the characterization of fiscal policy with respect to exogenous shocks and the cyclical behavior with respect to the historical shock decomposition of both tax rates.

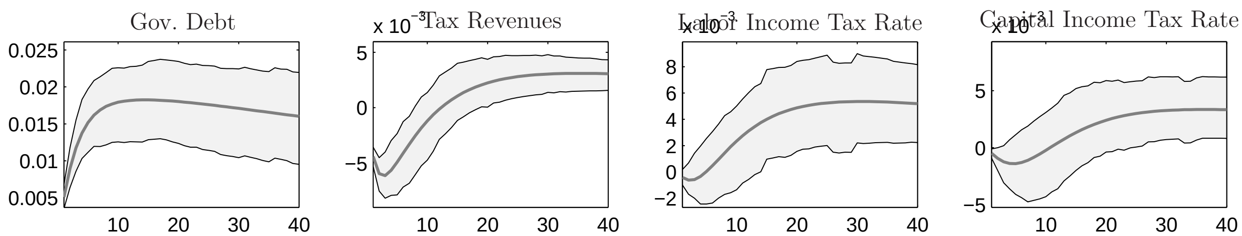
5.2 Impulse Response Analysis

In order to further investigate the effects of the estimated policy rules, we calculate the resulting Bayesian impulse-response functions to the non-fiscal policy structural shocks of the model. Figures 6(a)-6(d) display the results. The grey areas indicate the probability bands of the impulse response functions.

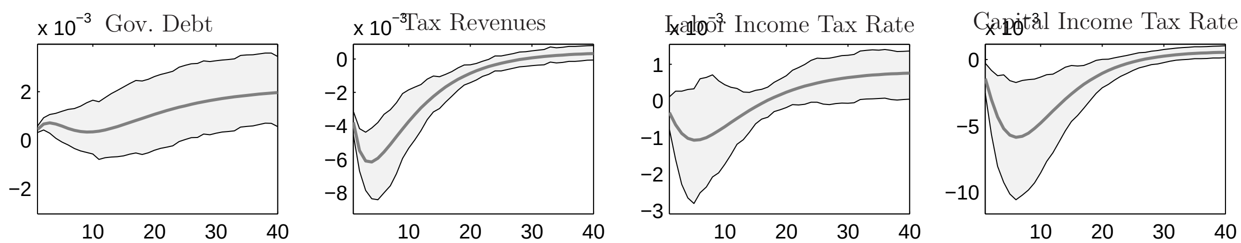
In line with the literature on fiscal policy, we define a counter-cyclical fiscal policy as



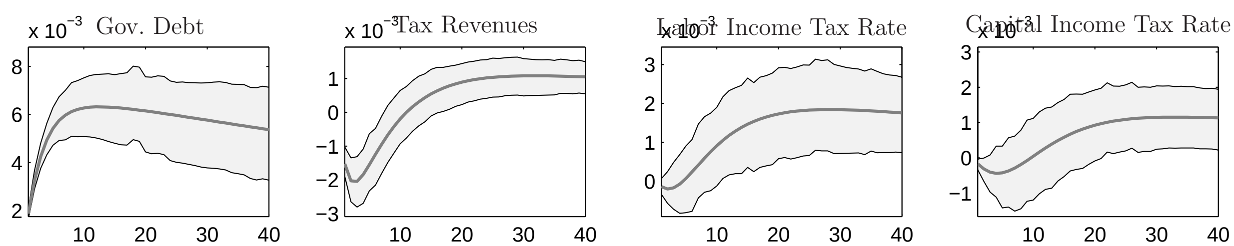
(a) Technology Shock.



(b) Risk premium shock.



(c) Investment-specific shock.



(d) Monetary policy shock.

Figure 6: Bayesian impulse responses with new feedback rules (solid) and old feedback rules.

being characterized by pro-cyclical tax rates relative to output. While η_{kI} introduces a counter-cyclical fiscal policy in the capital tax rule, the effect of η_{wh} on the labor tax rate is not so clear, since hours worked and output are not as highly correlated as investment and output.[11] The impulse-response functions suggest that the responses of the tax rates are pro-cyclical, i.e. fiscal policy acts counter-cyclically. This finding is in line with Cúrdia and Reis (2010).

5.3 Historical Decomposition

The specified and estimated policy rules represent the systematic response of the fiscal authority to the state of the economy. In Figure 7 and Figure 8 we plot the historical shock decomposition for the capital income tax rate and the labor income tax rate, respectively. The effects of the recessions as dated by the NBER, which are represented by the grey areas, explain to some extent the negative deviations from the steady state. It can be also observed that macroeconomic (non-policy) shocks (areas designated with right and left crossing lines) caused positive deviations from the steady-state. For the capital income tax rate this is notably the time between 1984 and 1988, as well as the mid-1990s boom. In these times, capital income was increasing, causing an increase in average capital income tax rates. For labor income tax rates, we find that the boom in the mid-1980s contributed positively.

We conclude that, especially, the estimated capital income tax rule takes into account automatic stabilizers during booms and recessions, which is in line with the empirical literature.

6 Conclusion

In this paper, we present a new approach for determining simple fiscal feedback rules in an estimated DSGE model with respect to the policymaker's objective function. We start by

[11] At the posterior mode, the correlations are 0.64 and 0.98 for the correlation of hours worked with output and investment and output, respectively.

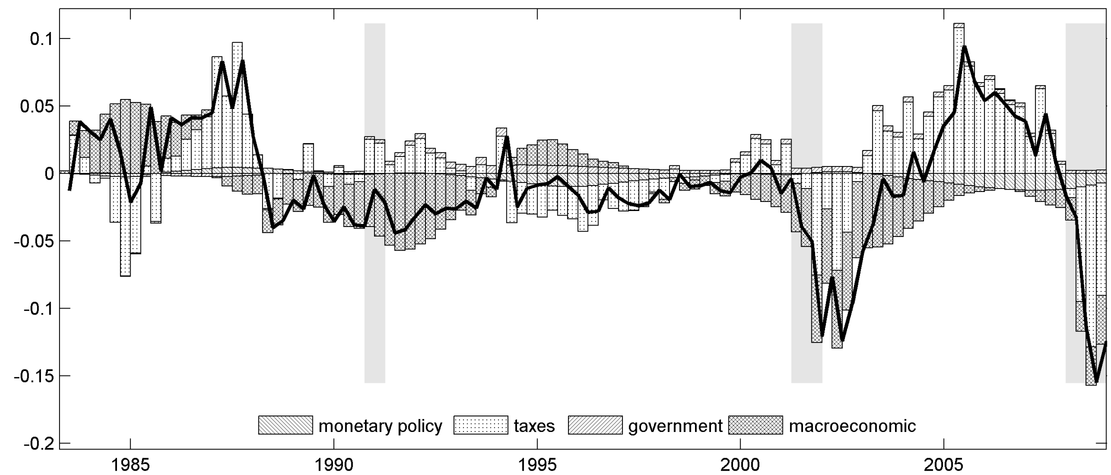


Figure 7: Historical decomposition of the observed capital income tax rate. The grey areas represent NBER recessions.

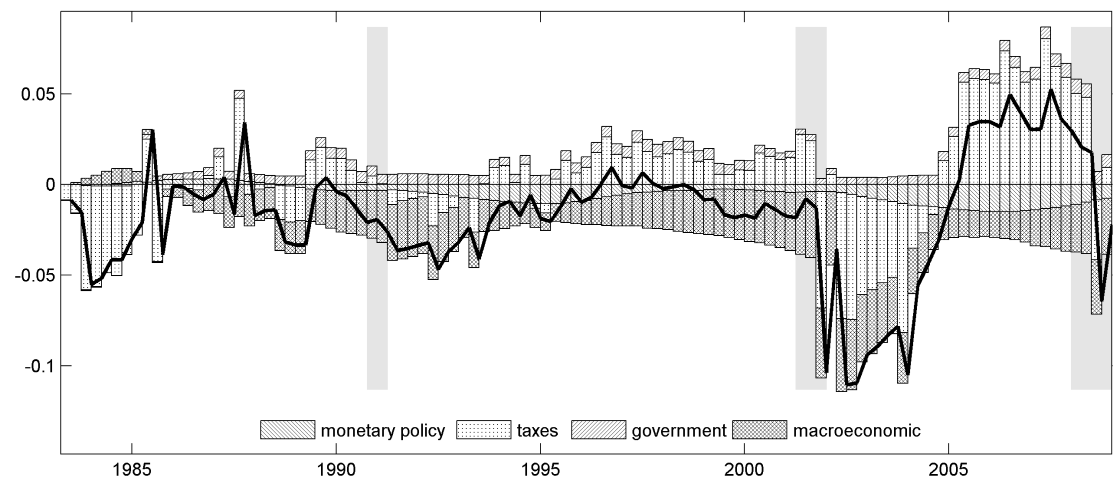


Figure 8: Historical decomposition of the observed labor income tax rate. The grey areas represent NBER recessions.

estimating a standard medium scale DSGE model to describe the behavior of the private sector. Considering the behavior of the government sector, we assume that the government responds to those variables in their feedback rules that influence the variable that is of interest to policymakers, welfare, at the optimal allocation to the largest extent. The feedback variables are determined at the optimal allocation. Given a sequence of exogenous shocks, we simulate time series for a set of variables that includes output, hours worked, private investment, the nominal interest rate, and private consumption. We are agnostic about the correct feedback variables in the policy rules. For this reason, we estimate simple linear policy rules for the tax rates to approximate the optimal dynamic behavior. The estimated policy rules are employed to compute the elasticities of the variance of welfare with respect to the feedback coefficients in the policy rules. The elasticities are calculated based on the approach proposed by Iskrev (2010). This allows us to rank the feedback variables according to their importance for welfare's variance.

As an application, we specify the rules for the tax rate on labor income and the tax rate on capital income. Both rules contain feedback coefficients on lagged tax rates, and government debt. In addition, a feedback coefficient on hours worked is important for the rule of labor income tax rates and a feedback coefficient on investment is important for the rule of capital income tax rates. All feedback coefficients are identified as being significantly different from zero. The estimated impulse response functions imply counter-cyclical fiscal policy. This finding emphasizes the importance of carefully modeled fiscal feedback rules, because it is in contrast to standard ad-hoc policy rules (e.g. in the spirit of Leeper, 1991) and in line with Cúrdia and Reis (2010). The authors demonstrate that standard medium-scale DSGE models are misspecified with respect to fiscal policy. In addition, the importance of carefully modeled fiscal policy is further stressed by the historical shock decomposition of the average tax rates. Our estimated tax rules captures the cyclical behavior of fiscal policy. It thereby helps us to further understand and quantify the stabilizing role of the fiscal authority and distinguish between automatic stabilizing fiscal policy and exogenous tax shocks.

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A Data Description

The frequency of all final data used is quarterly.

Real GDP: This series is *BEA NIPA table 1.1.6 line 1*.

Nominal GDP: This series is *BEA NIPA table 1.1.5 line 1*.

Implicit GDP Deflator: The implicit GDP deflator is calculated as the ratio of nominal GDP to real GDP.

Private Consumption: This series is defined as private consumption of non-durable goods (*BEA NIPA table 1.1.5 line 5*) and private consumption of services (*BEA NIPA table 1.1.5 line 6*).

Private Investment: This series is gross private domestic investment (*BEA NIPA table 1.1.5 line 7*) plus private consumption of durable goods (*BEA NIPA table 1.1.5 line 4*).

Government Transfers: This series is defined as net current transfers, net capital transfers, and subsidies (*BEA NIPA table 3.2 line 32*). In addition, net current transfers are current transfer payments (*BEA NIPA table 3.1 line 22*) minus current transfer receipts (*BEA NIPA table 3.2 line 15*), net capital transfers are defined as the difference between capital transfer payments (*BEA NIPA table 3.2 line 43*) and capital transfer receipts (*BEA NIPA table 3.2 line 39*).

Nominal Interest Rate: The quarterly nominal interest rate is defined as the averages of daily figures of the fed funds fate obtained from the Board of Governors of the Federal Reserve System.

Inflation: The gross inflation rate is defined as the change in the implicit GDP deflator.

Population: This series is defined as the civilian noninstitutional population (CNP16OV), age 16 and over provided by the U.S. Department of Labor: Bureau of Labor Statistics: *source: http://research.stlouisfed.org/fred2/series/CNP16OV?cid=104.*

Tax Rates: Capital and labor tax rates are calculated following Jones (2002), where the labor tax rate is computed as:

$$\tau^w = \frac{FIT + SIT}{W + PRI/2 + CI} \cdot \frac{(W + PRI/2)}{EC + PRI/2} + \frac{CSI}{EC + PRI/2} \ ,$$

where CSI denotes total contributions to social insurance (*BEA NIPA table 3.1 line 7*), EC denotes compensation of employees (*BEA NIPA table 1.12 line 2*), FIT denotes federal personal current taxes (*BEA NIPA table 3.2 line 3*), SIT denotes state and local personal current taxes (*BEA NIPA table 3.3 line 3*), PRI denotes proprietors' income (*BEA NIPA table 1.12 line 9*), W denotes wage and salary accruals (*BEA NIPA table 1.12 line 3*), and CI is capital income. Capital income is defined as rental income (*BEA NIPA table 1.12 line 12*), corporate profits (*BEA NIPA table 1.12 line 13*), interest income (*BEA NIPA table 1.12 line 18*), and $PRI/2$. The average capital income tax rate is computed as:

$$\tau^k = \frac{FIT + SIT}{W + PRI/2 + CI} \cdot \frac{CI}{CI + PT} + \frac{CT + PT}{CI + PT} \ ,$$

where CT denotes taxes on corporate income (*BEA NIPA table 3.1 line 5*) and PT denotes property taxes (*BEA NIPA table 3.3 line 8*).

Government Tax Revenues: Tax revenues, x, are defined as the sum of capital income taxes and taxes on labor. They are computed as:

$$x = \tau^w \cdot (EC + PRI/2) + \tau^k \cdot (CI + PT) \, .$$

B Appendix (Not for Publication)

B.1 Prior, Calibration, and Data

Description	Symbol	Value
Discount factor	β	0.9926
Capital share	α	0.3
Depreciation rate	δ	0.025
Price markup	$\theta_p/(\theta_p - 1)$	1.2
Wage markup	$\theta_w/(\theta_w - 1)$	1.1
Annualized interest rate	$\bar{R}$	1.0418
Annual inflation	$\bar{\pi}$	1.0112
Ratio of government consumption to output	$\bar{c}^g/\bar{y}$	0.18
Ratio of government transfers to output	$\bar{\tau}^l/\bar{y}$	-0.07
Steady-state capital tax rate	$\bar{\tau}_k$	0.3572
Steady-state labor tax rate	$\bar{\tau}_w$	0.2343

Table 4: Parameter calibration.

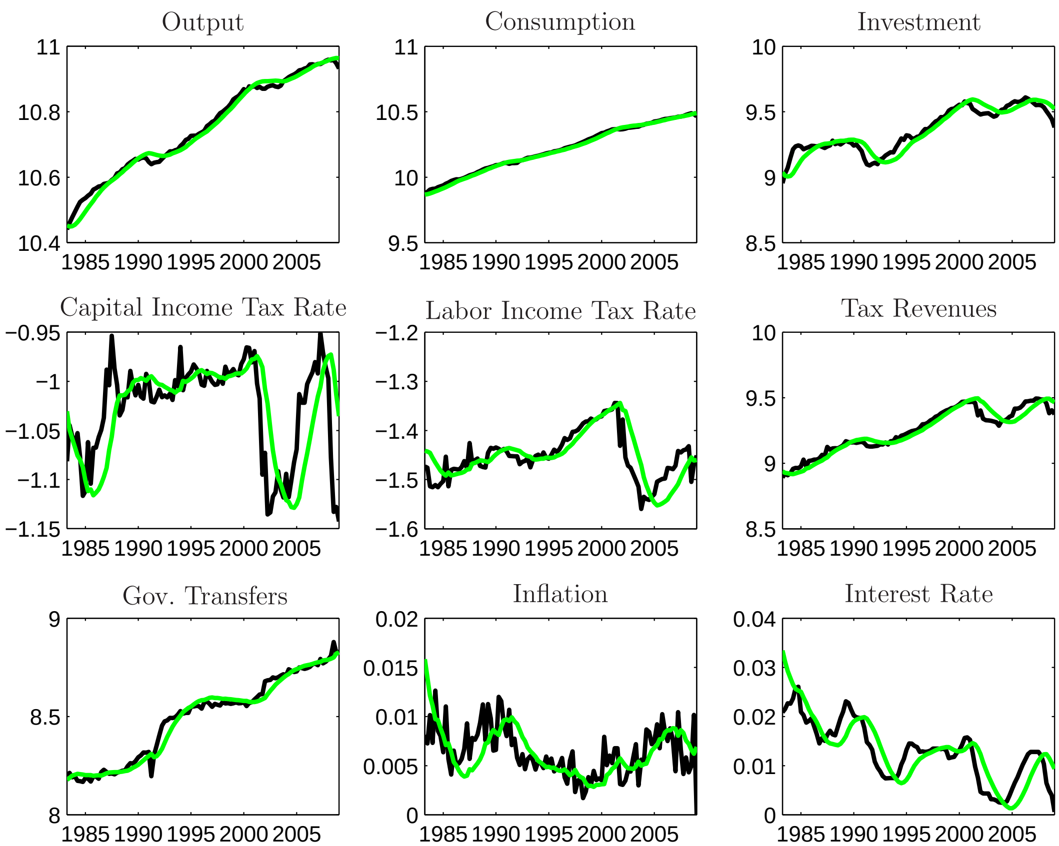

Figure 9: Raw time series (black) and and corresponding trend (green).

Parameter	Symbol	Domain	Density	Para(1)	Para(2)
Inv. intertemp. subst. elasticity	σ_c	$\mathbb{R}^+$	Gamma	1.75	0.5
Inverse Frisch elasticity	σ_l	$\mathbb{R}^+$	Gamma	2.0	0.5
Habit persistence	h	$[0,1)$	Beta	0.5	0.15
Calvo parameter prices	γ_p	$[0,1)$	Beta	0.5	0.15
Calvo parameter wages	γ_w	$[0,1)$	Beta	0.5	0.15
Investment adjustment cost	ν	$\mathbb{R}^+$	Gamma	4	1.25
Capital utilization cost	σ_u	$\mathbb{R}^+$	Gamma	2	0.5
Interest rate AR coefficient	ρ_R	$[0,1)$	Beta	0.8	0.1
Interest rate inflation coefficient	ρ_π	$\mathbb{R}^+$	Gamma	1.7	0.1
Interest rate output coefficient	ρ_y	$\mathbb{R}$	Gamma	0.125	0.05
Labor tax AR coefficient	ρ_w	$[0,1)$	Beta	0.85	0.1
Labor tax debt coefficient	η_{wb}	$\mathbb{R}^+$	Gamma	0.4	0.2
Capital tax AR coefficient	ρ_k	$[0,1)$	Beta	0.85	0.1
Capital tax debt coefficient	η_{kb}	$\mathbb{R}^+$	Gamma	0.4	0.2
Lump-sum tax AR coefficient	ρ_{τ^l}	$[0,1)$	Beta	0.85	0.1
Adjustment costs AR coefficient	ρ_i	$[0,1)$	Beta	0.85	0.1
Technology AR coefficient	ρ_z	$[0,1)$	Beta	0.85	0.1
Public consumption AR coefficient	ρ_{cg}	$[0,1)$	Beta	0.85	0.1
S.d. adjustment costs shock	ϵ_i	$\mathbb{R}^+$	InvGam	0.01	4.0
S.d. technology shock	ϵ_z	$\mathbb{R}^+$	InvGam	0.01	4.0
S.d. finance premium shock	ϵ_q	$\mathbb{R}^+$	InvGam	0.01	4.0
S.d. monetary policy shock	ϵ_m	$\mathbb{R}^+$	InvGam	0.01	4.0
S.d. wage tax shock	ϵ_{τ^w}	$\mathbb{R}^+$	InvGam	0.01	4.0
S.d. capital tax shock	ϵ_{τ^k}	$\mathbb{R}^+$	InvGam	0.01	4.0
S.d. lump-sum tax shock	ϵ_{τ^l}	$\mathbb{R}^+$	InvGam	0.01	4.0
S.d. public consumption shock	ϵ_{cg}	$\mathbb{R}^+$	InvGam	0.01	4.0
S.d. measurement error taxes	ϵ_{tax}	$\mathbb{R}^+$	InvGam	0.01	4.0

Table 5: Prior distribution of model parameters. Para(1) and Para(2) correspond to means and standard deviations for the Beta, Gamma, Inverted Gamma, and Normal distribution.

B.2 Estimation Private Sector

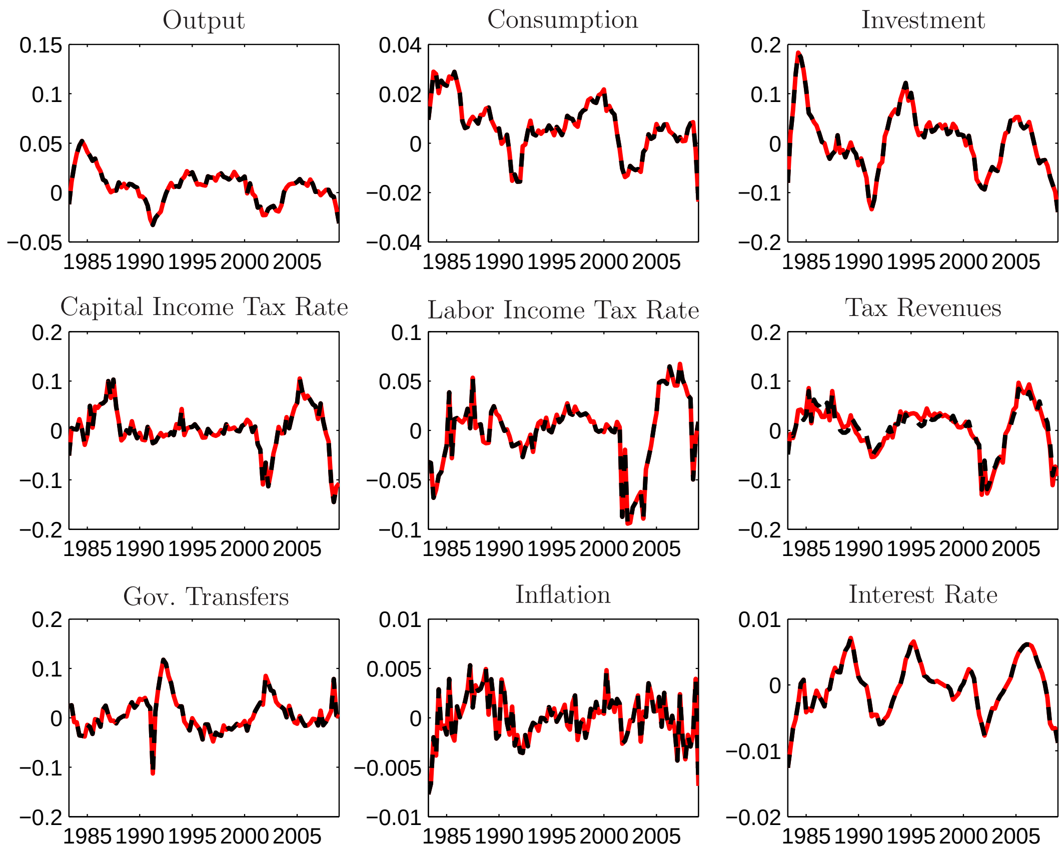

Figure 10: Historical variables (red) and smoothed variables (black) at posterior mode.

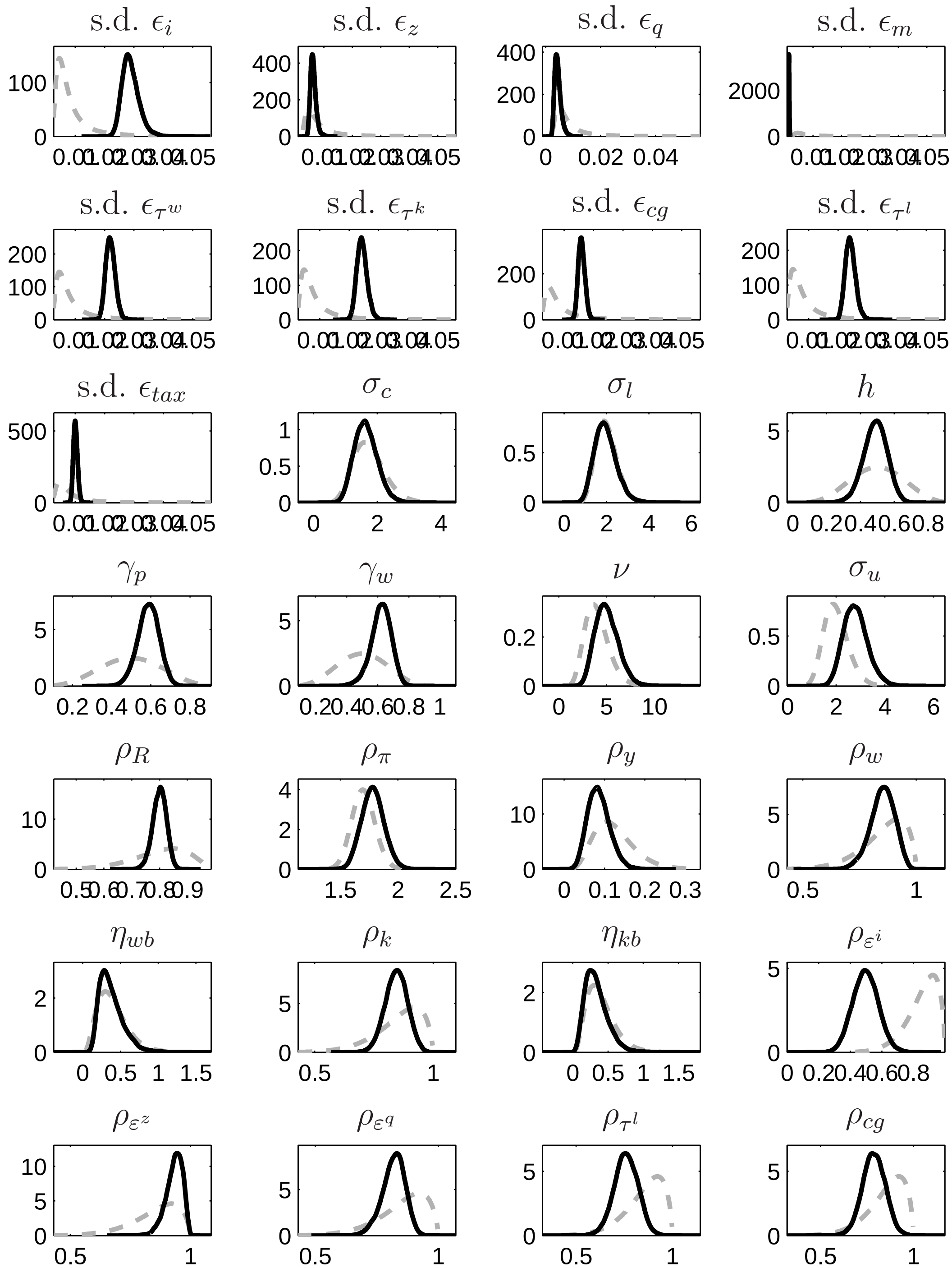

Figure 11: Prior (grey dashed) and posterior (black solid) distribution of the model's parameters (private sector estimation).

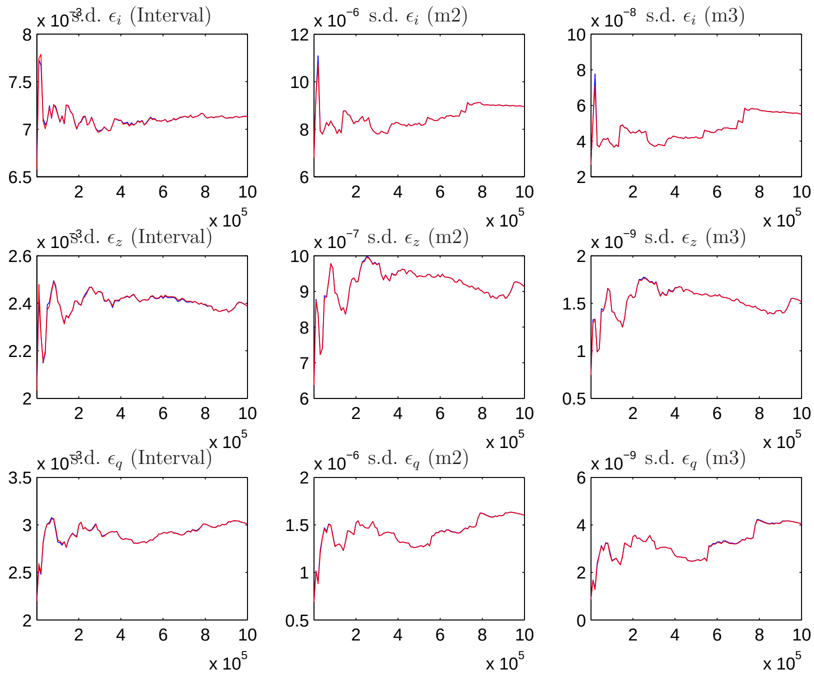

Figure 12: Univariate convergence diagnostics for the Metropolis-Hastings. The first, second and third columns are respectively the criteria based on the eighty percent interval, the second and third moments.

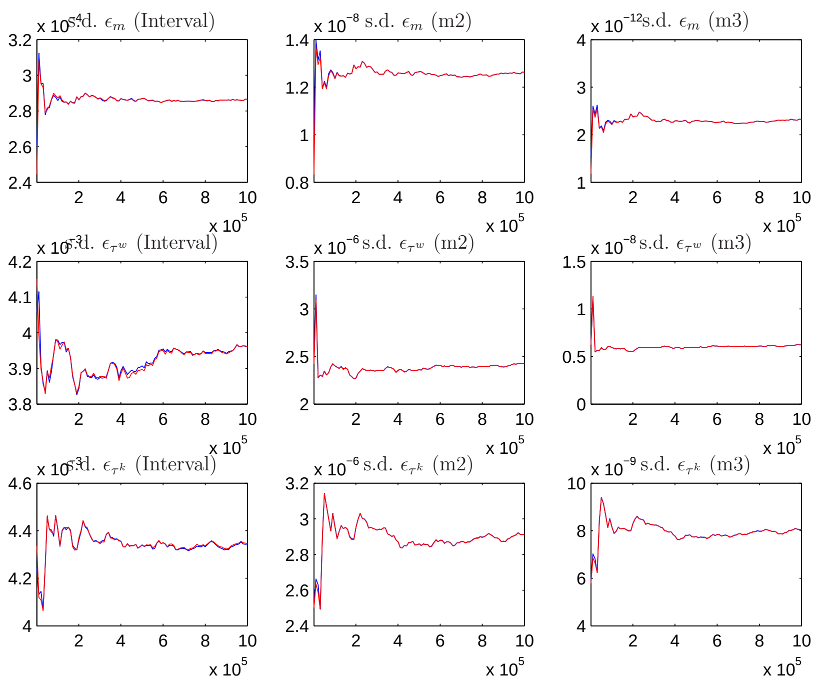

Figure 13: Univariate convergence diagnostics for the Metropolis-Hastings. The first, second and third columns are respectively the criteria based on the eighty percent interval, the second and third moments.

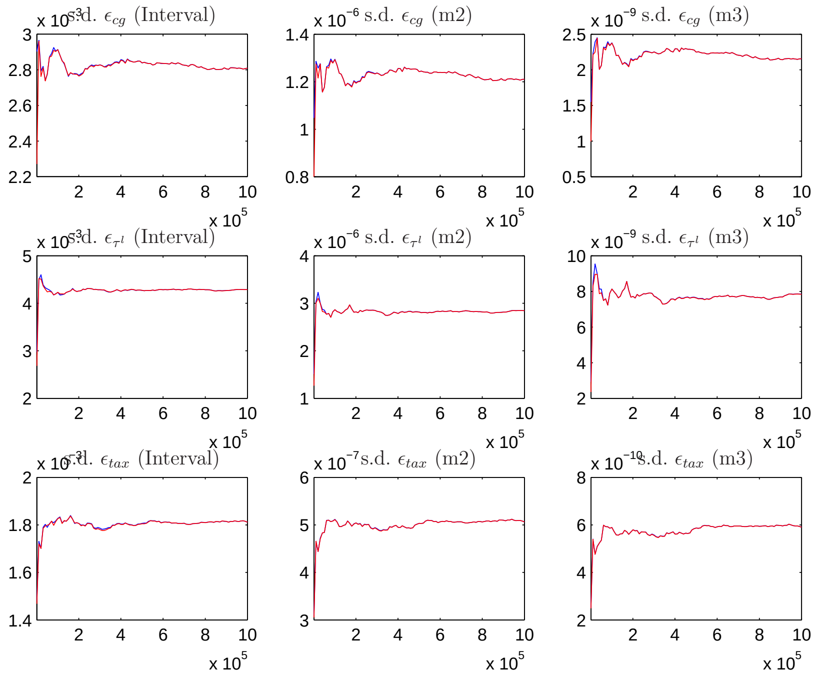

Figure 14: Univariate convergence diagnostics for the Metropolis-Hastings. The first, second and third columns are respectively the criteria based on the eighty percent interval, the second and third moments.

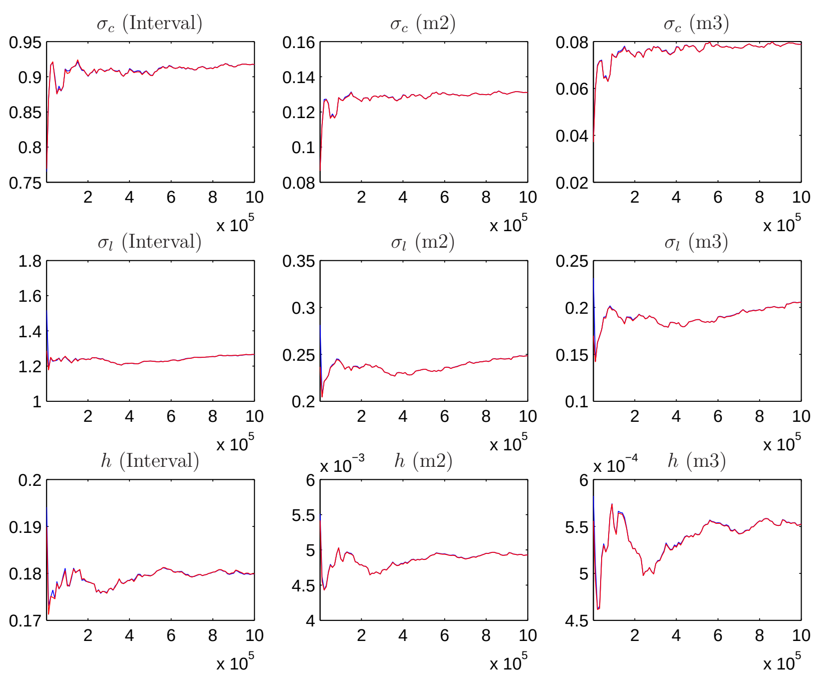

Figure 15: Univariate convergence diagnostics for the Metropolis-Hastings. The first, second and third columns are respectively the criteria based on the eighty percent interval, the second and third moments.

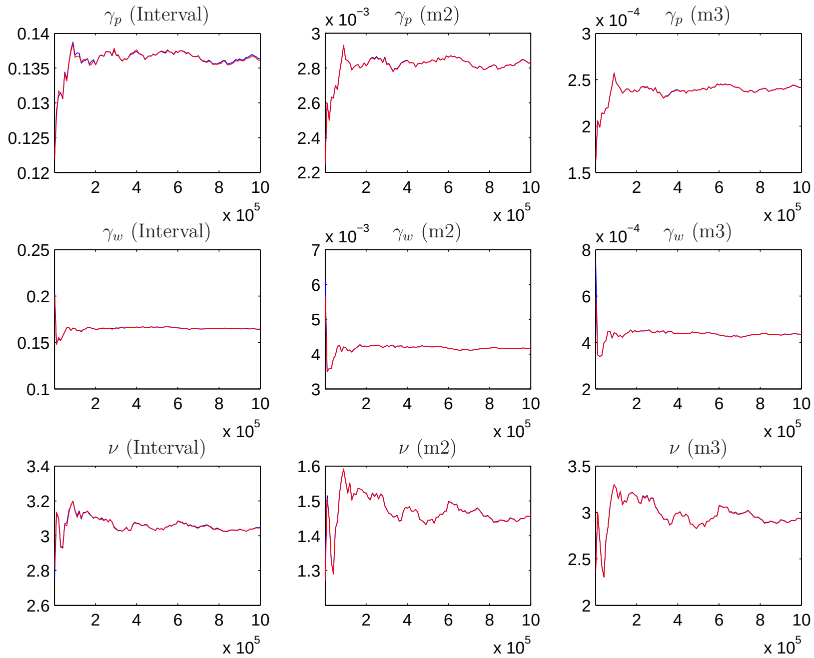

Figure 16: Univariate convergence diagnostics for the Metropolis-Hastings. The first, second and third columns are respectively the criteria based on the eighty percent interval, the second and third moments.

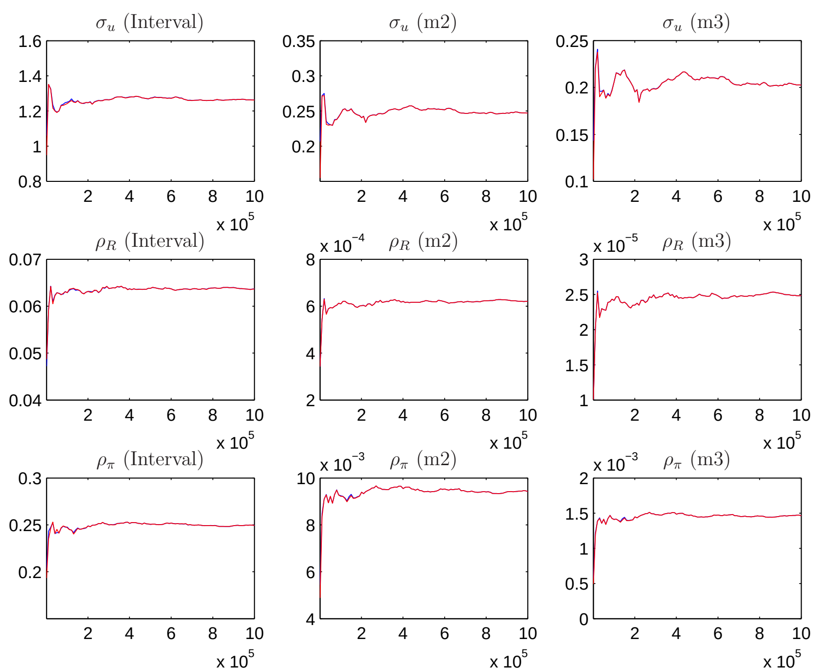

Figure 17: Univariate convergence diagnostics for the Metropolis-Hastings. The first, second and third columns are respectively the criteria based on the eighty percent interval, the second and third moments.

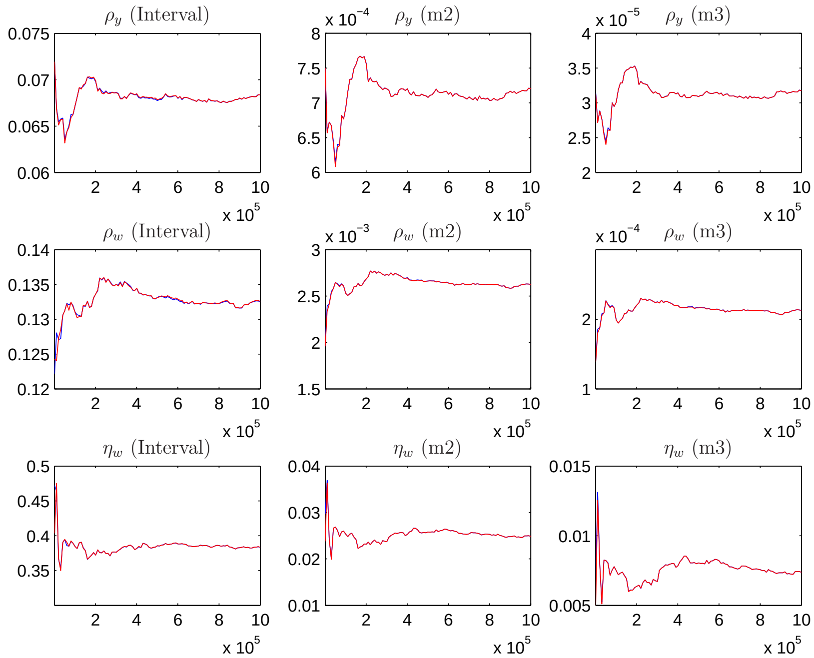

Figure 18: Univariate convergence diagnostics for the Metropolis-Hastings. The first, second and third columns are respectively the criteria based on the eighty percent interval, the second and third moments.

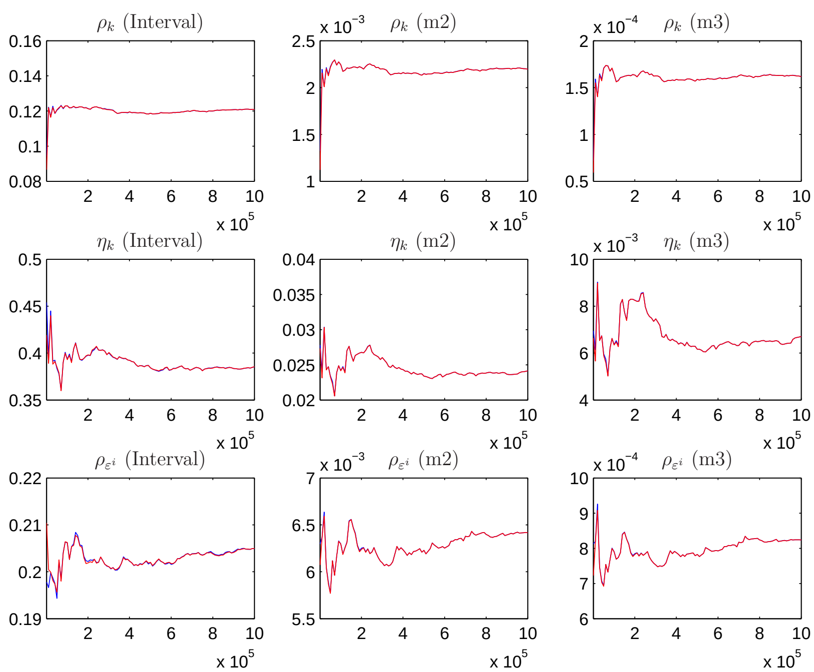

Figure 19: Univariate convergence diagnostics for the Metropolis-Hastings. The first, second and third columns are respectively the criteria based on the eighty percent interval, the second and third moments.

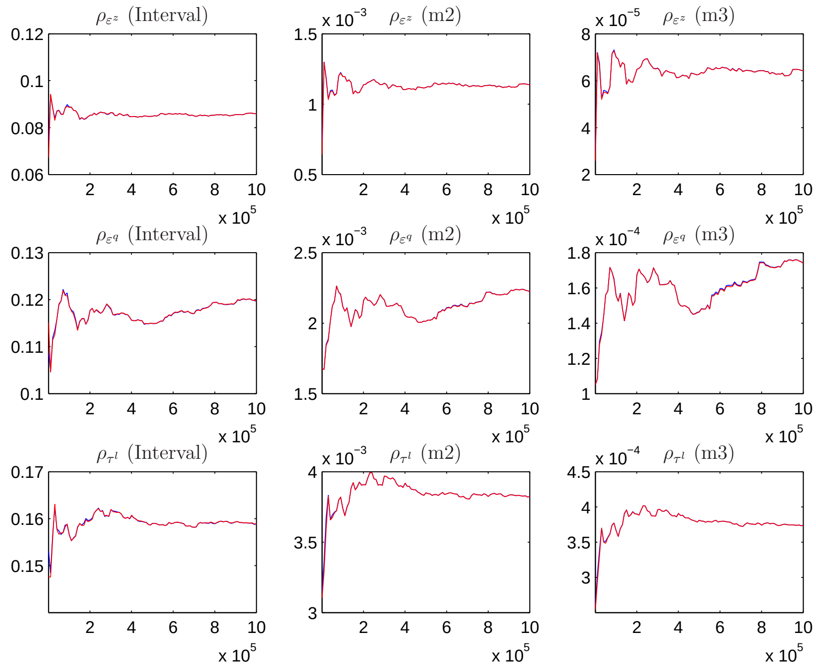

Figure 20: Univariate convergence diagnostics for the Metropolis-Hastings. The first, second and third columns are respectively the criteria based on the eighty percent interval, the second and third moments.

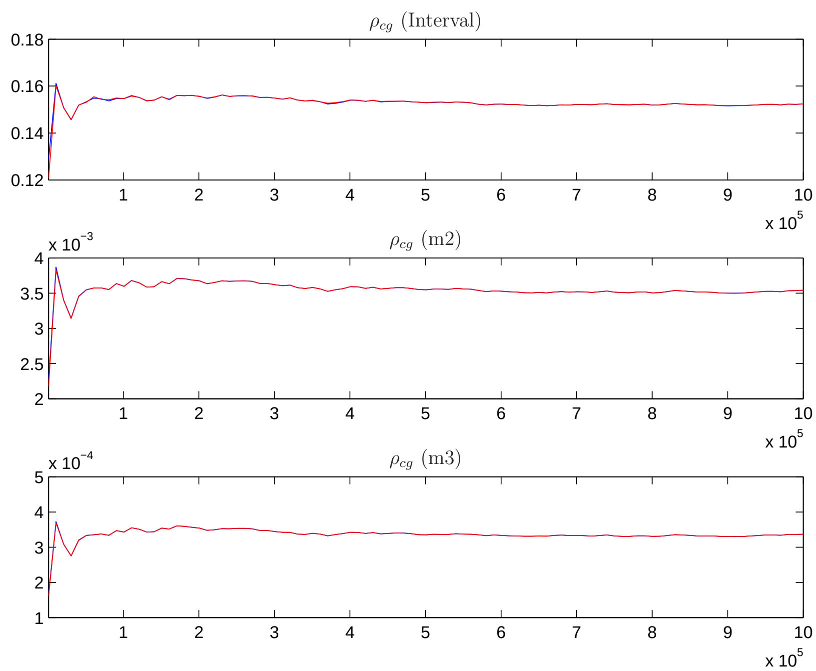

Figure 21: Univariate convergence diagnostics for the Metropolis-Hastings. The first, second and third columns are respectively the criteria based on the eighty percent interval, the second and third moments.

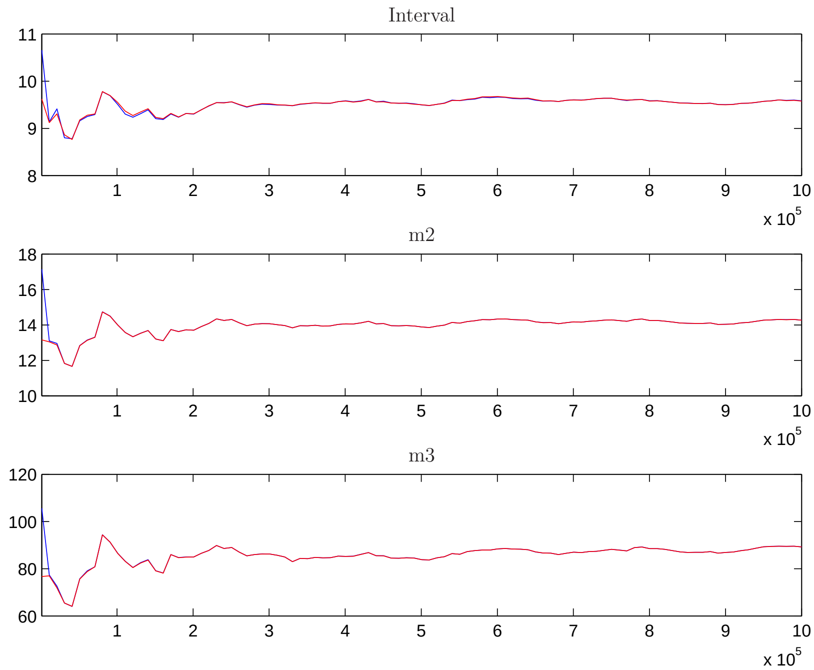

Figure 22: Multivariate convergence diagnostics for the Metropolis-Hastings. The first, second and third rows are respectively the criteria based on the eighty percent interval, the second and third moments. The different parameters are aggregated using the posterior kernel.

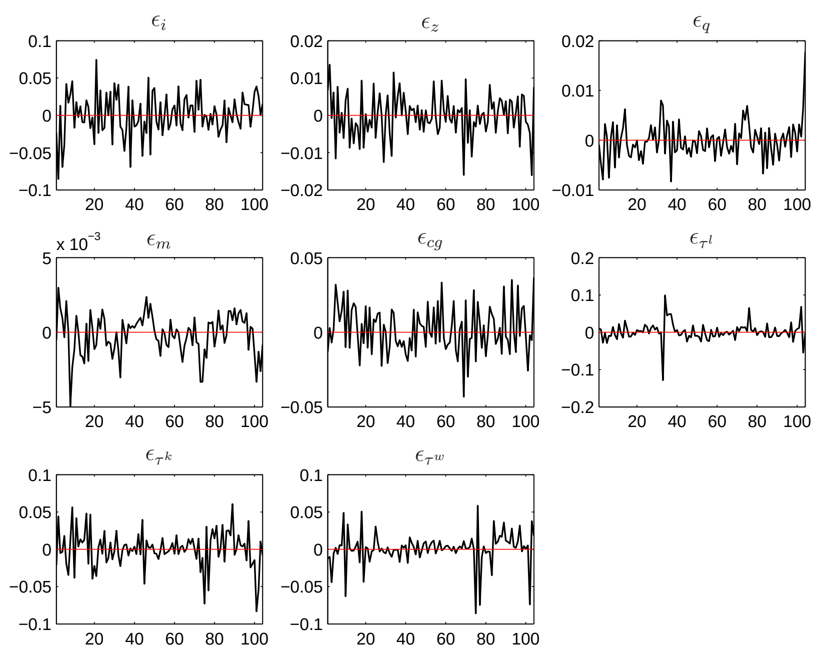

Figure 23: Smoothed shocks for private sector estimation.

B.3 Optimal Policy

Feedback Parameter	Symbol	Prior Mean	Prior S.d.	Mode	S.d.	T-value
			TAX RATE ON LABOR INCOME			
Labor tax rate	ρ_w	0.800	0.1000	0.7109	0.0700	10.1565
Capital	η_{wk}	0.000	0.5000	0.0178	0.2122	0.0841
Debt	η_{wb}	0.200	0.5000	0.0277	0.0207	1.3342
Output	η_{wy}	0.000	0.5000	-0.5485	0.4894	1.1209
Consumption	η_{wc}	0.000	0.5000	-0.4193	0.6607	0.6346
Hours worked	η_{wh}	0.000	0.5000	-1.8995	0.3433	5.5329
Wage rate	η_{ww}	0.000	0.5000	1.2964	0.3629	3.5726
Investment	η_{wI}	0.000	0.5000	0.0380	0.2202	0.1727
Inflation	$\eta_{w\pi}$	0.000	0.5000	-0.1058	0.5004	0.2113
Nominal interest rate	η_{wR}	0.000	0.5000	-0.2221	0.4950	0.4486
			TAX RATE ON CAPITAL INCOME			
Capital tax rate	ρ_k	0.800	0.1000	0.8370	0.0582	14.3751
Capital	η_{kk}	0.000	0.5000	-0.0346	0.4830	0.0716
Debt	η_{kb}	-0.200	0.5000	0.2294	0.0976	2.3495
Output	η_{ky}	0.000	0.5000	-0.4015	0.4928	0.8148
Consumption	η_{kc}	0.000	0.5000	-0.1838	0.4973	0.3695
Hours worked	η_{kh}	0.000	0.5000	-0.5180	0.4903	1.0564
Wage rate	η_{kw}	0.000	0.5000	0.2308	0.4923	0.4689
Investment	η_{kI}	0.000	0.5000	-1.1503	0.4397	2.6160
Inflation	$\eta_{k\pi}$	0.000	0.5000	0.0533	0.5005	0.1065
Nominal interest rate	η_{kR}	0.000	0.5000	-0.0206	0.4999	0.0412

Table 6: Posterior mode maximization of optimized feedback coefficients.

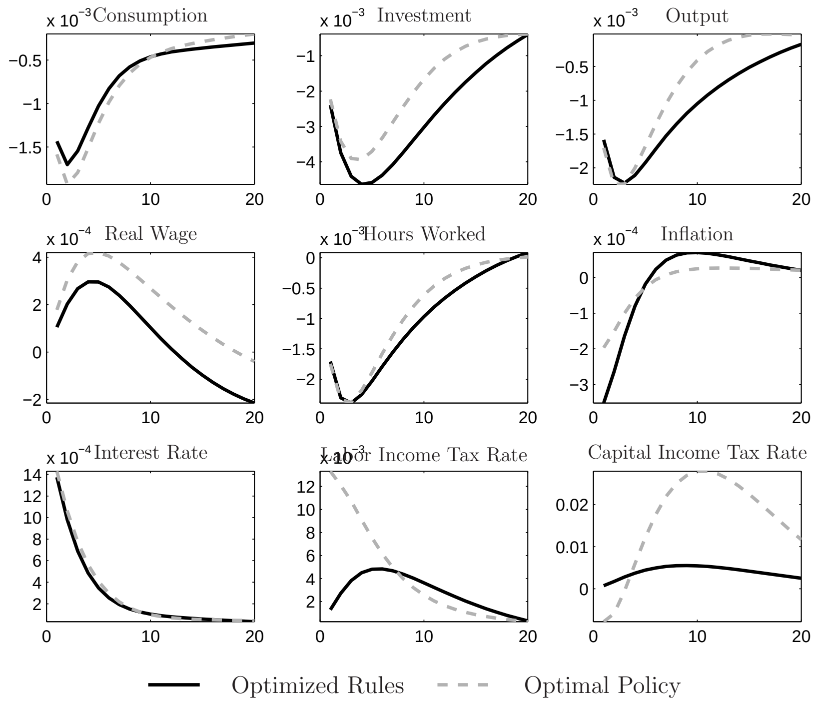

Figure 24: Impulse responses under optimized rules (solid) and optimal policy (dashed). Monetary policy shock.

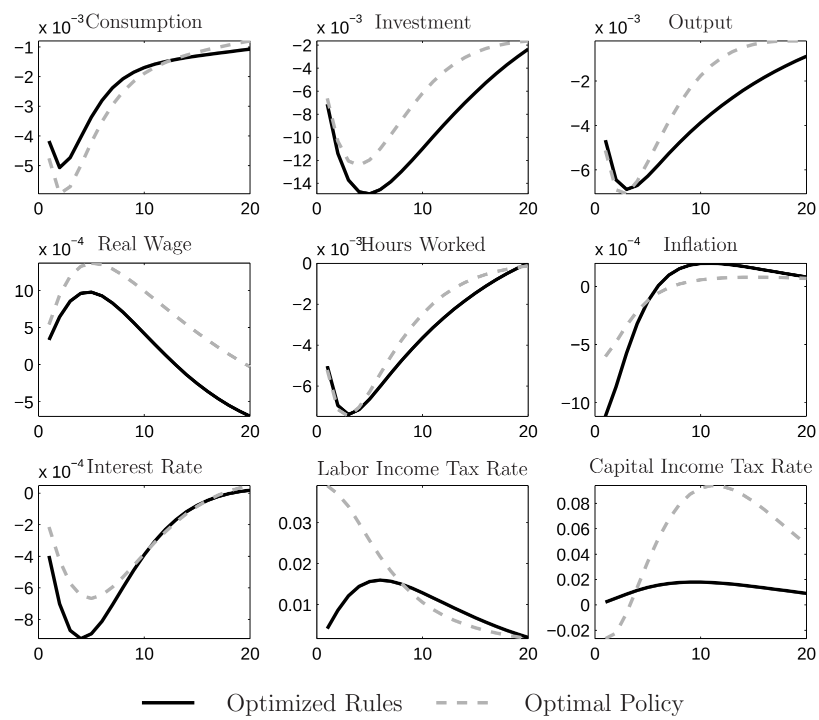

Figure 25: Impulse responses under optimized rules (solid) and optimal policy (dashed). Risk premium shock.

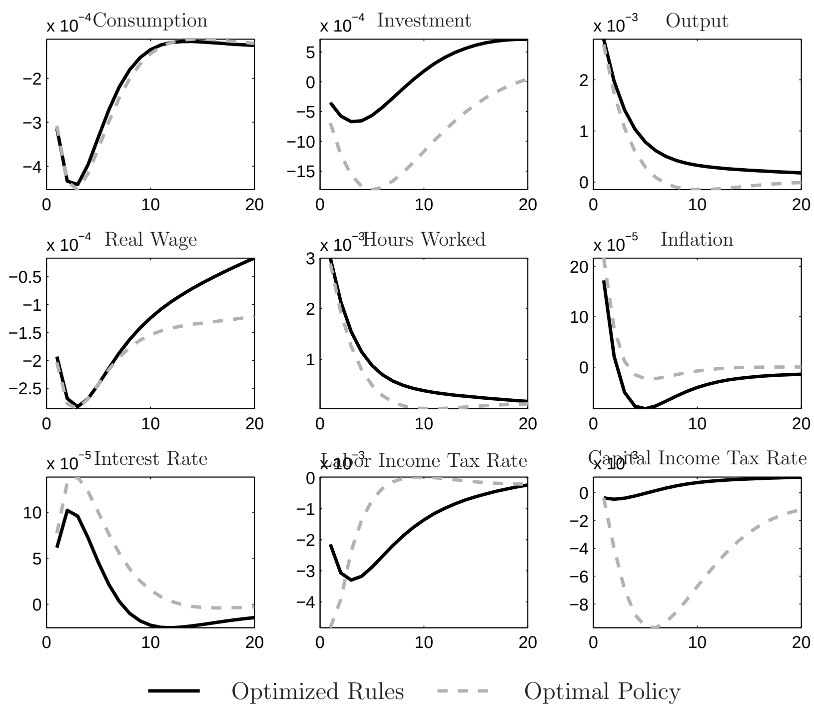

Figure 26: Impulse responses under optimized rules (solid) and optimal policy (dashed). Government consumption shock.

B.4 Estimation Fiscal Rules

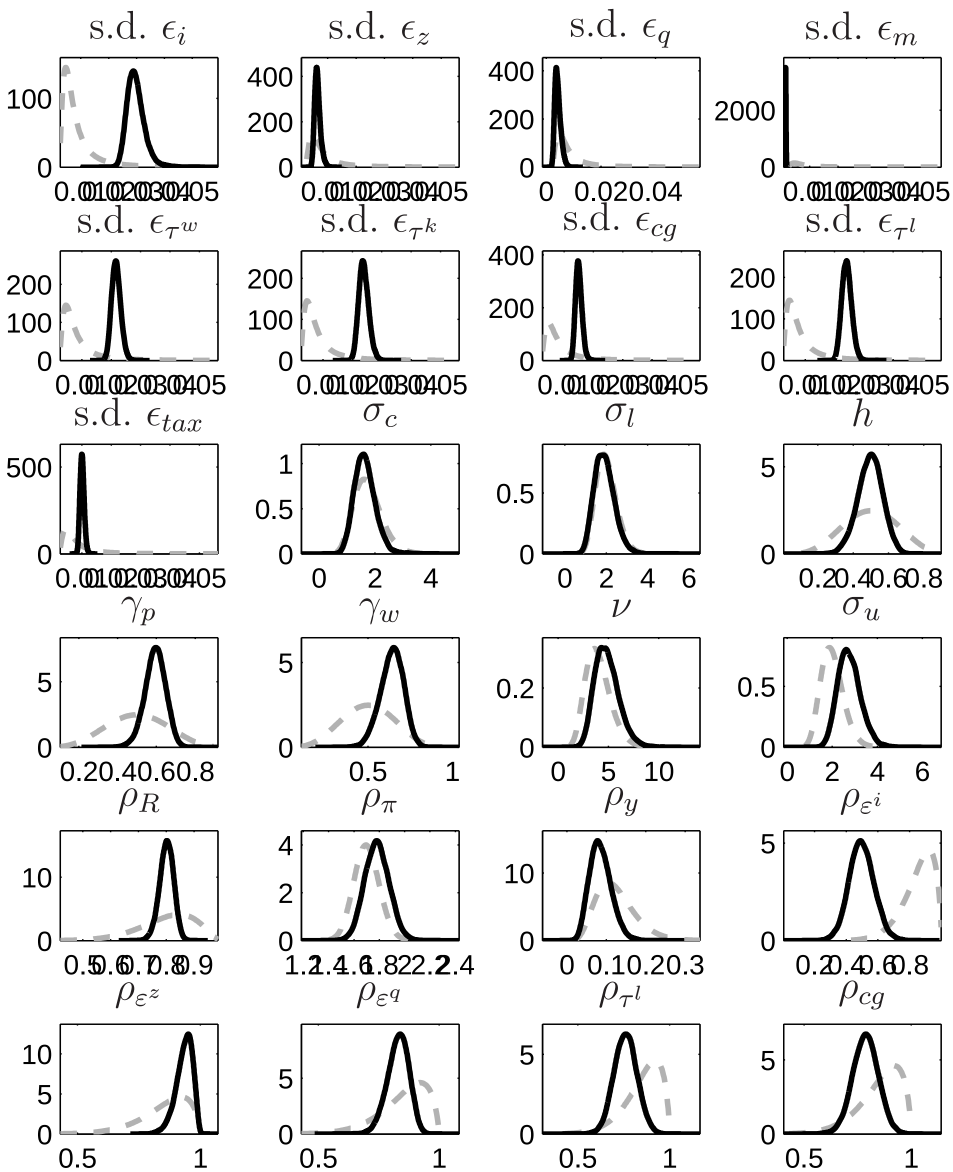

Figure 27: Prior (grey dashed) and posterior (black solid) distribution for the final model estimation.

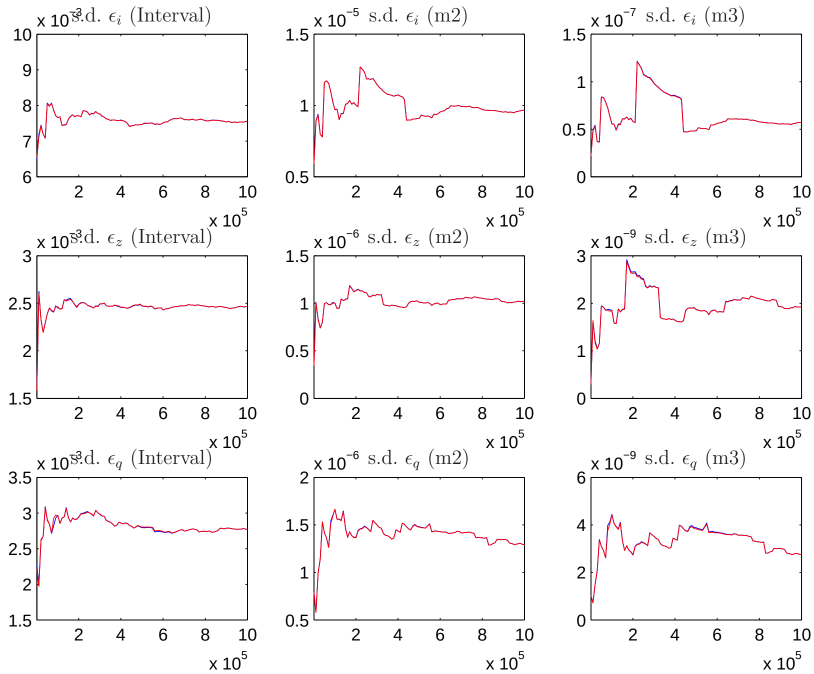

Figure 28: Univariate convergence diagnostics for the Metropolis-Hastings. The first, second and third columns are respectively the criteria based on the eighty percent interval, the second and third moments.

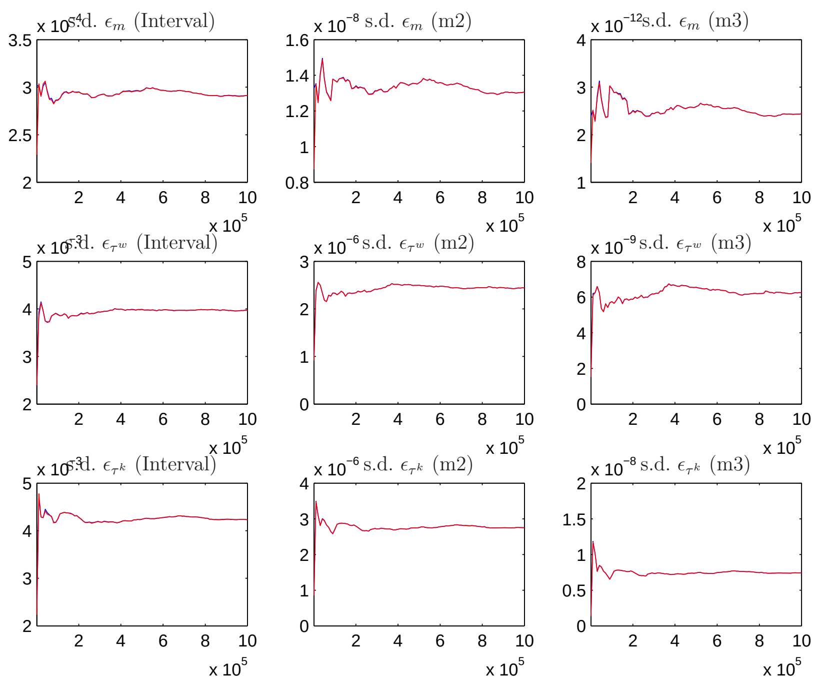

Figure 29: Univariate convergence diagnostics for the Metropolis-Hastings. The first, second and third columns are respectively the criteria based on the eighty percent interval, the second and third moments.

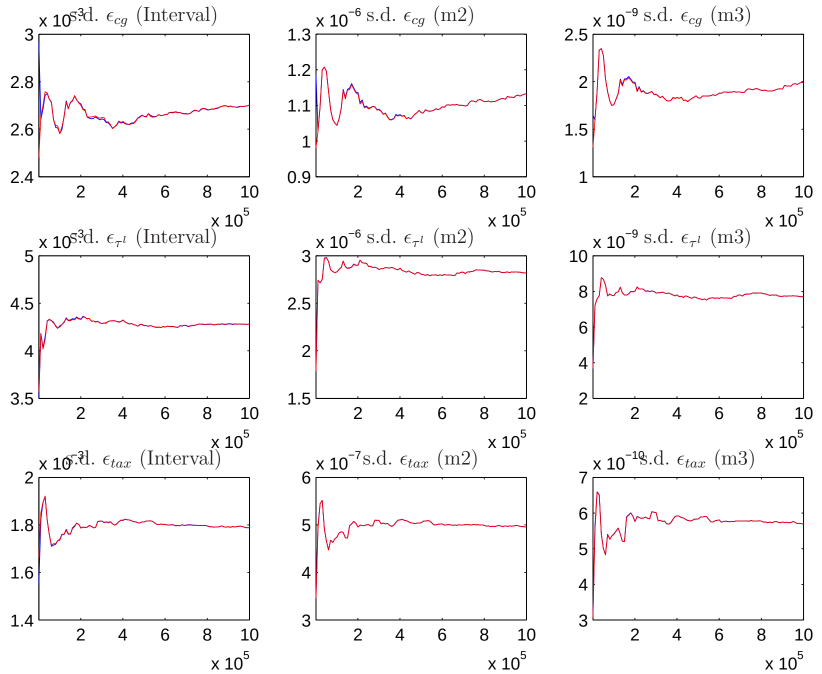

Figure 30: Univariate convergence diagnostics for the Metropolis-Hastings. The first, second and third columns are respectively the criteria based on the eighty percent interval, the second and third moments.

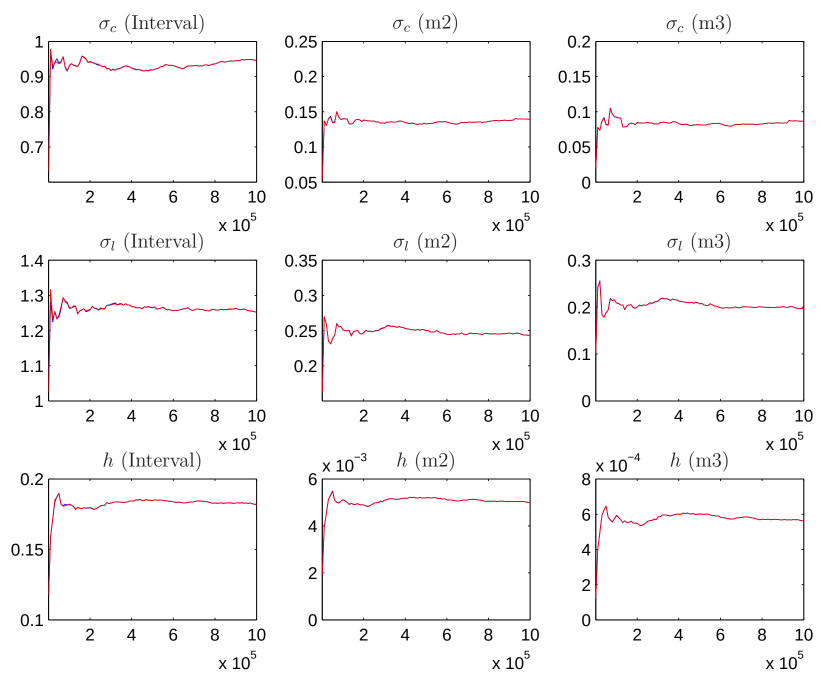

Figure 31: Univariate convergence diagnostics for the Metropolis-Hastings. The first, second and third columns are respectively the criteria based on the eighty percent interval, the second and third moments.

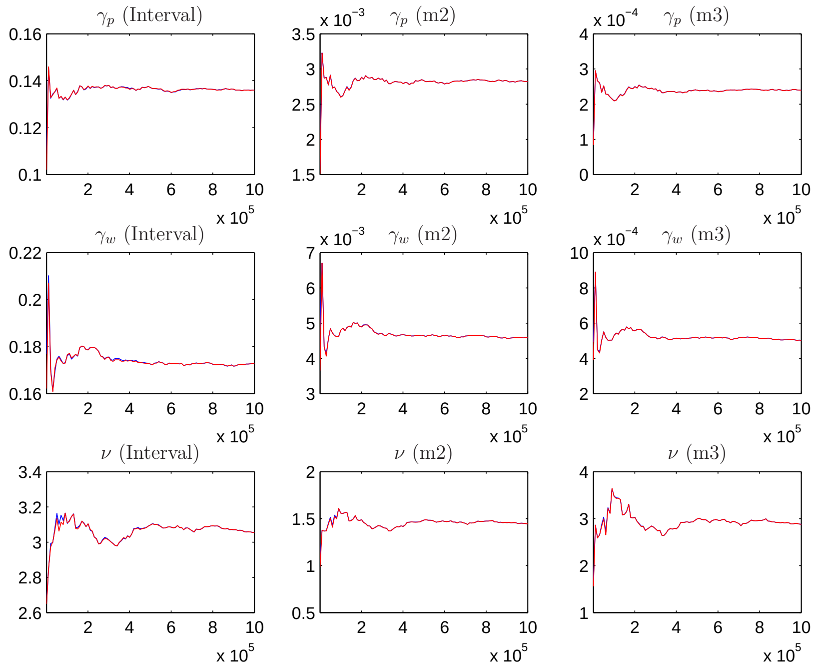

Figure 32: Univariate convergence diagnostics for the Metropolis-Hastings. The first, second and third columns are respectively the criteria based on the eighty percent interval, the second and third moments.

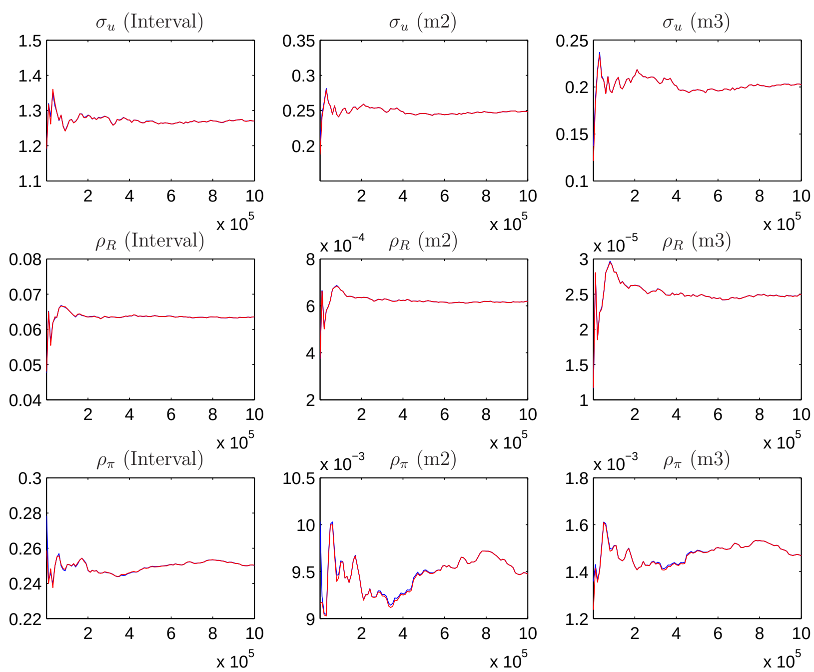

Figure 33: Univariate convergence diagnostics for the Metropolis-Hastings. The first, second and third columns are respectively the criteria based on the eighty percent interval, the second and third moments.

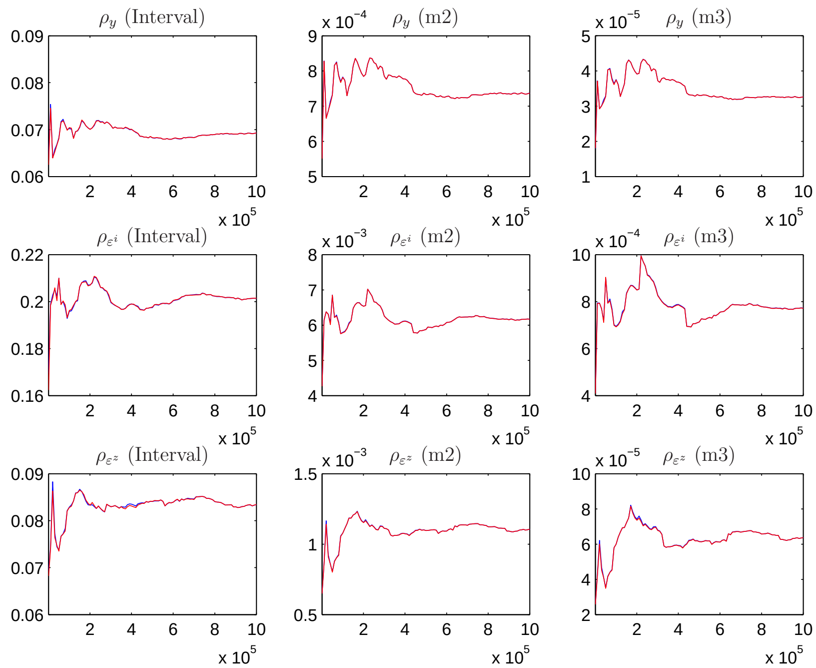

Figure 34: Univariate convergence diagnostics for the Metropolis-Hastings. The first, second and third columns are respectively the criteria based on the eighty percent interval, the second and third moments.

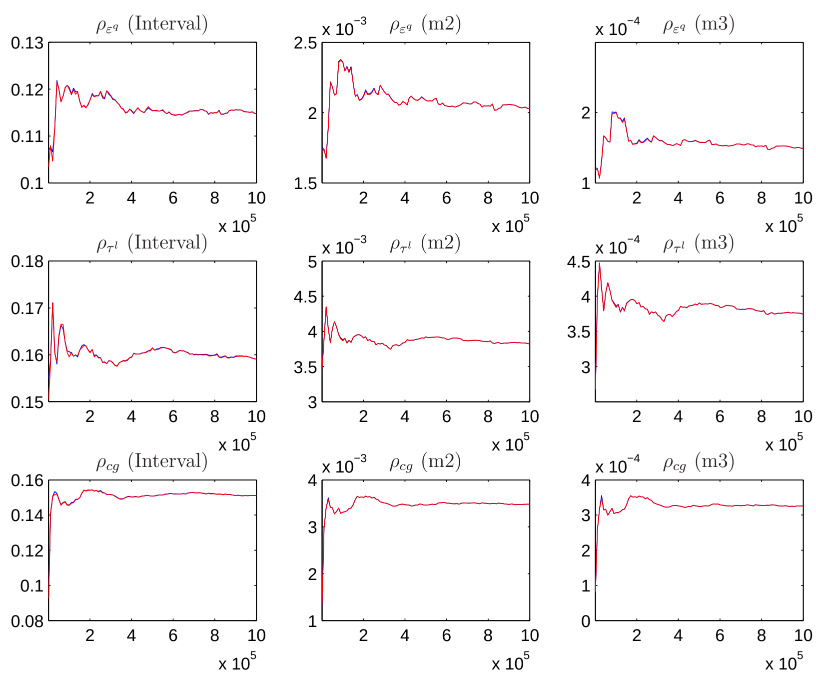

Figure 35: Univariate convergence diagnostics for the Metropolis-Hastings. The first, second and third columns are respectively the criteria based on the eighty percent interval, the second and third moments.

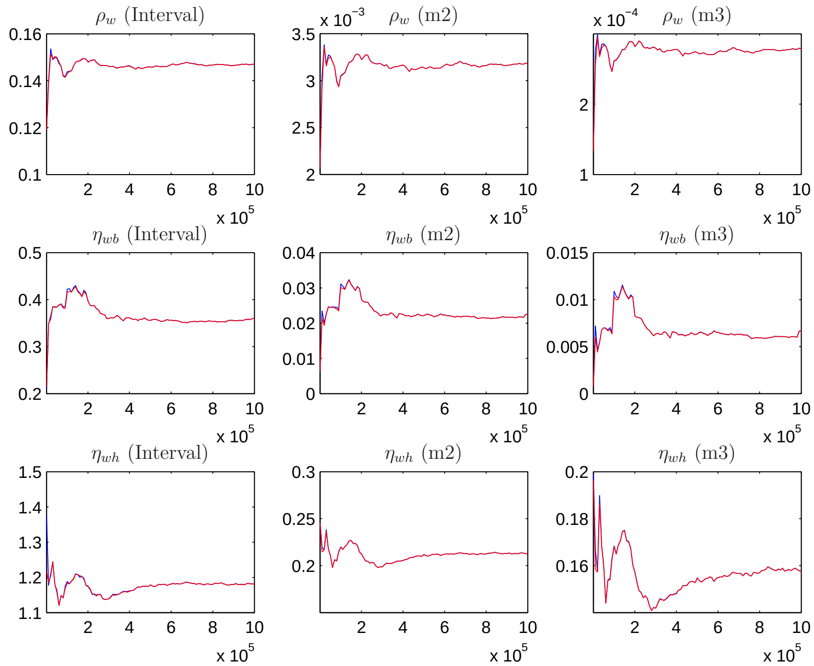

Figure 36: Univariate convergence diagnostics for the Metropolis-Hastings. The first, second and third columns are respectively the criteria based on the eighty percent interval, the second and third moments.

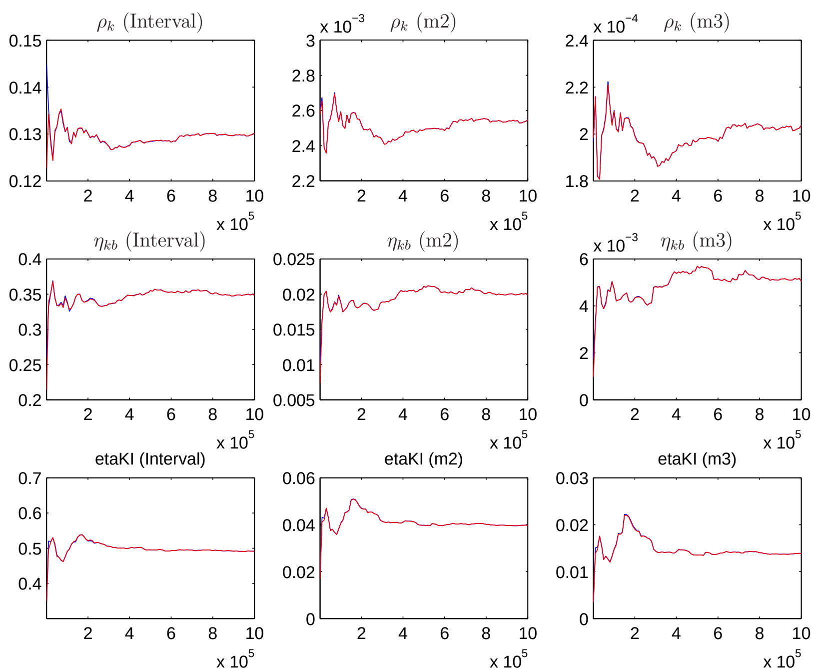

Figure 37: Univariate convergence diagnostics for the Metropolis-Hastings. The first, second and third columns are respectively the criteria based on the eighty percent interval, the second and third moments.

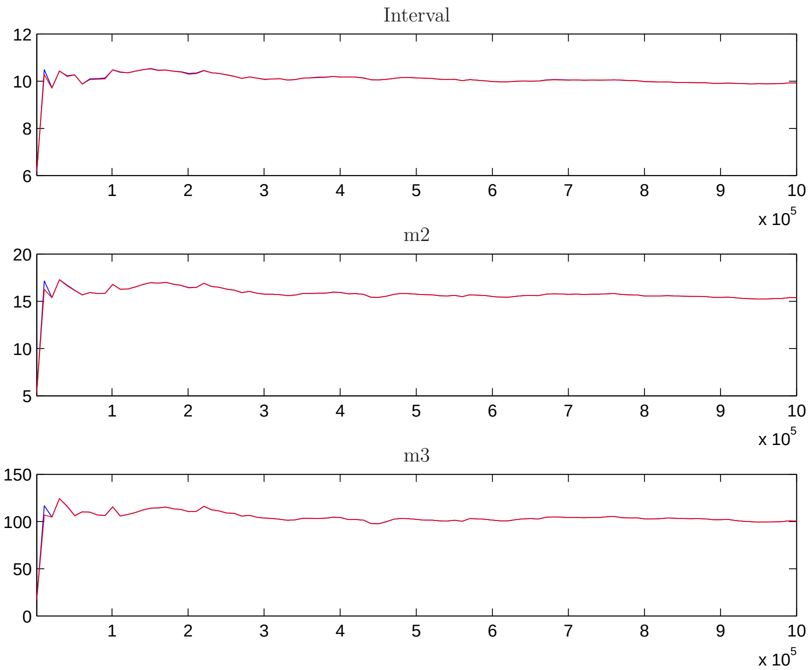

Figure 38: Multivariate convergence diagnostics for the Metropolis-Hastings. The first, second and third rows are respectively the criteria based on the eighty percent interval, the second and third moments. The different parameters are aggregated using the posterior kernel.

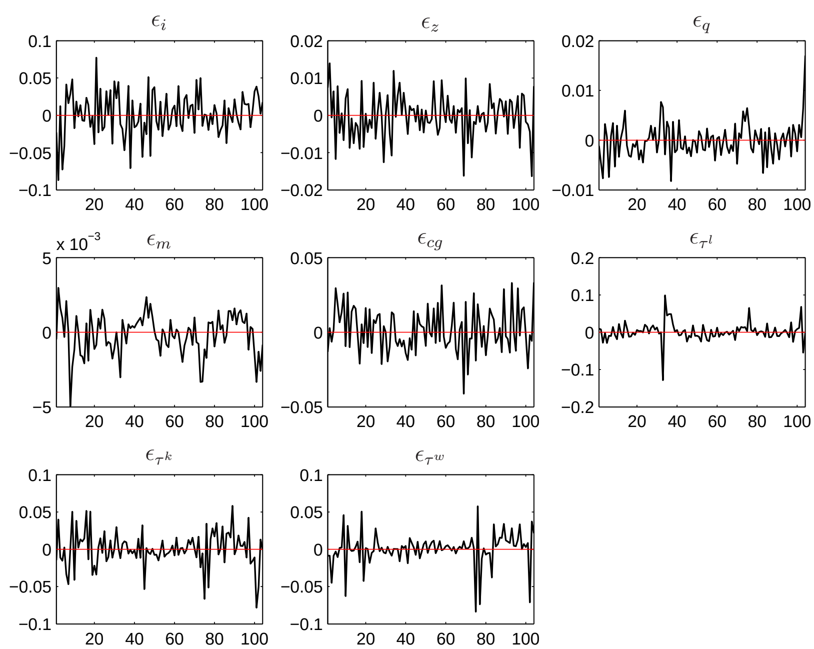

Figure 39: Smoothed shocks for final model estimation.