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### Discussion paper

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**Estimating US Fiscal and Monetary Interactions  
in a Time Varying VAR**

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# Estimating US Fiscal and Monetary Interactions in a Time Varying VAR

Eddie Gerba and Klemens Hauzenberger\*

## Abstract

We contribute to the growing empirical literature on monetary and fiscal interactions by applying a sign restriction identification scheme to a structural TVP-VAR in order to disentangle and evaluate the policy shocks and policy transmissions. This in turn allows us to study the Great Recession in a consistent fashion. Four facts stand out from our findings. We observe significant differences in the endogenous responses to shocks in particular between the Volcker period and the Great Recession, and find that monetary policy reacts more aggressively during Volcker chairmanship and fiscal policy during the Great Recession to stabilize the economy. Second, impulse responses confirm that there is a high degree of interactions between monetary and fiscal policies over time. Third, in the forecast error variance decomposition we find that while government revenues largely influence decisions on government spending, government spending does not influence tax decisions. Fourth and final, our analysis of the fiscal transmission channel reveals that tax cuts, because of their crowding-in effects, are more effective in expanding output than government spending rises, since the tax multiplier is higher and more persistent. In light of the current recession and the zero lower bound of the interest rate, tax cuts can, by providing the right incentives to the private sector, result in high and very persistent growth in output if private agent expectations regarding the length and the financing structure of the fiscal expansion are delicately managed jointly by the two authorities.

JEL: C11, C32, E52, E61, E62, E63

Keywords: time varying parameter VAR, sign restrictions, Markov-Chain Monte Carlo, US economic structure, fiscal transmission channel

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# 1 Introduction

Locating the appropriate degree of interaction between fiscal and monetary policy plays an important role in ensuring economic stability. This has been most evident during the Great Recession in the US, when on one hand, the Fed reduced the Federal Funds rate by more than 500 basis points from August 2007 and injected a vast amount of liquidity into the financial system through the three quantitative easings (the first announced in November 2008, the second in November 2010, and the third in September 2012). Worried additionally by the persistently high long-term yields, the Fed launched moreover two ‘Operation twists’ (first running between September 2011 and June 2012, and the second from July to December 2012) whereby the Fed exchange their shorter-dated liabilities for longer-term Treasuries in order to bring the prices of longer-term bonds up, and the yields down, while generating the opposite effect on the short-term bonds. In parallel, the US Congress passed two fiscal packages, the Economics Stimulus Act of 125 billion dollar in 2008, and the American Recovery and Reinvestment Act of 787 billion dollar in early 2009, and one fiscal reform, the Jump-Start Our Business Start-Ups Act in March 2012, a law intended to encourage funding of small businesses by easing a number of securities regulations. Their joint economic impact is, however, still unclear. The theoretical and empirical literature on fiscal-monetary interactions is equally inconclusive and points in multiple directions. It goes so far that there is no consensus to whether a (systematic or regular) coordination between fiscal and monetary policy ever existed in the US.

Against this background, our interest lies in examining in-depth the actual policy interactions over the past three decades (1979-2012). We allow for changes in the US economic structure, and jointly study the effectiveness of monetary and fiscal policy in stabilizing the economy. Further, we will examine the fiscal transmission mechanism and monetary pass-through over time and provide empirical evidence on the structural shocks that have been most important in explaining the fluctuations of the US economy over this period.

There is a richer theoretical literature on fiscal-monetary interactions compared to the empirical.<sup>1</sup>That is an outcome that has evolved from the difficulty of com-

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<sup>1</sup>They find that it is very important to jointly study the fiscal and monetary policy in order to determine the equilibrium. Chadha and Nolan (2007) find that Taylor-like monetary and fiscal rules are a good representation of US and UK stabilization policies. Neglecting the role of automatic stabilizers in designing the optimal policies has immediate effects for the optimal monetary policy. So, for instance, a passive fiscal policy requires a large long-run response of the policy rate to

paring theoretical and empirical results. When appropriate care is taken for the diverse complications inherent in macroeconomic time series, such as unit roots, and in the case of policy decisions, real time versus revised data, then results from standard theoretical and empirical models strongly diverge (Reade and Stehn, 2008, and Juselius, 2007). As a consequence, the empirical models have departed from their theoretical counterparts.

Several interesting insights have emerged from the empirical fiscal-monetary models. Fragetta and Kirsanova (2007) model policy interactions in the UK, Sweden and the US. Using Leeper's (1991) definition of leader and follower they investigate whether one or the other authority has acted as a leader. They find no evidence for dominance in the US, and suggest that the two authorities ignore each other. On the other end, Muscatelli et al. (2004), using generalized methods of moments, estimate a forward-looking new-Keynesian model for the US. They find that depending on the shocks considered, the nature of fiscal-monetary interactions has been different. For business cycle shocks, monetary and fiscal policies act as compliments, meaning that when monetary policy is tightened, so is fiscal policy. However, for a monetary shock, a tighter monetary policy results in a relaxed fiscal policy, hence acting as substitutes. Reade and Stehn (2008) also find evidence for policy interactions in the US, since both policies are countercyclical, and each of them takes into account the actions of the other. Conversely, Melitz (2002) finds that monetary and fiscal policies move in opposite directions, thus behave as substitutes. On the economic effects of the two policies, Melitz (2002) and Muscatelli et al. (2004) find that spending responds in a destabilizing manner to current output, while taxes behave in a stabilizing fashion.<sup>2</sup>For monetary policy, Muscatelli et al. (2004) detect a stabiliz-

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inflation for the previous optimum to be reached (Chadha and Nolan (2007), Annicchiarico et al (2012)). Davig and Leeper (2010) estimate Markov-switching policy rules for the US and find that the monetary and fiscal policy fluctuate between active and passive behavior. In a New-Keynesian model, this results in positive spending multipliers, but the intensity of the multiplier depends on the degree of crowding out in private consumption and investment that the policy causes. Moreover, Annicchiarico et al (2012) argue that the fiscal expansions tend to generate an intertemporal trade-off. The positive fiscal shocks are expansionary in the short-run, but depending on the monetary policy rule pursued, are likely to generate persistent adverse effects in the medium-run. Baxter and King (1993), and Davig and Leeper (2010) find that the negative effects of fiscal policy result from the higher tax burden in the future. Finally, Galí and Monacelli (2008) show that in a currency union with country-specific shocks and nominal rigidities, inflation should be stabilized at the union level, while the countercyclical fiscal policy should be country-specific when the latter seek to limit the size of the domestic output gap and inflation differentials resulting from idiosyncratic shocks.

<sup>2</sup>Muscatelli et al. (2004) find, however, that spending responds in a stabilizing manner to lagged output.

ing role of the interest rate relative to output, and Reade and Stehn (2008) show that monetary policy has a stronger impact on economic activity compared to fiscal policy.

In short, the empirical results are inconclusive, and depend strongly on the methodology used. Nevertheless, the majority of them point at least toward an implicit coordination between monetary and fiscal authorities, and indicate a greater effectiveness of monetary policy in dampening output volatility.

We use the recently established structural time varying parameter VAR (henceforth TVP-VAR) to examine US policies between 1979:I-2012:II. The structural TVP-VAR was put forward by Cogley and Sargent (2005) and Primiceri (2005) to establish and examine the different monetary policy regimes that the US has undergone since the post-war period. While they observe some deviation in the impulse responses during the oil-shocks and early Volcker period, for the remaining sample, they find insignificant time-variation. Moreover, they note that most of the variation is attributed to the variance of the residuals, and not to the coefficients. Separately, Kirchner et al. (2010) and Pereira and Lopes (2010) have used a TVP-VAR to examine the effect of fiscal policy shocks. While the former has employed a recursive assumption to identify spending shocks, the latter use the method of Blanchard and Perotti (2002) to identify tax and spending shocks.<sup>3</sup>More recently, Hauzenberger (2012) has performed a similar analysis for a fiscal TVP-VAR with a special focus on debt dynamics but which does not include the monetary side.

The study closest to ours is Rossi and Zubairy (2011).<sup>4</sup>They jointly consider monetary and fiscal shocks in their analysis of the US economy, and find that conditioning monetary policy and fiscal policy on each other is crucial for producing unbiased estimates of the business cycle drivers. Additionally, by means of variance decompositions, they find that monetary policy shocks are most important for explaining business cycle fluctuations in output, consumption and hours, while fiscal policy shocks are most important for explaining cyclical volatilities over the medium-term. Nevertheless their study was performed using a fixed-coefficient structural VAR and so the contribution of each shock is invariant during that sample period. In the same manner, the fiscal transmission channel is not allowed to alter with changing

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<sup>3</sup>See also Fatas and Mihov (2001) for recursive assumptions.

<sup>4</sup>Mountford and Uhlig (2009) falls to a certain extent into this category. They identify both monetary and fiscal shocks, but concentrate their analysis on the effects of fiscal policy and not the interaction between the two policies. Monetary policy is identified in order to isolate its effects from fiscal policy.

economic conditions. Our TVP-VAR will correct for this omission by allowing the shocks and the fiscal transmission to vary over time.

Our empirical approach is based on a five variable version of the Bayesian TVP-VAR technique with stochastic volatility. The variables we include are output, government spending, net taxes, a short-term interest rate and inflation. We identify four shocks—business cycle, monetary policy, spending, and taxes—through theoretically robust sign restrictions. There is a fifth shock in this model (a residual shock), but because the shock is activated by innovations in one of the other model variables, it is not identified and therefore does not have a structural interpretation. Moreover, the sign restrictions are a partial identification method and there is therefore no necessity to identify as many fundamental shocks as variables in our model (see, e.g., Uhlig, 2005). Further, identifying a business cycle shock jointly with the other shocks is crucial to separate automatic effects of output fluctuations from discretionary policy measures (Mountford and Uhlig, 2009). In the context of policy interactions, the sign restrictions framework does not oblige us to impose timing assumptions regarding the fiscal-monetary interaction, since the interactions can be contemporaneous or lagged, thus implying more adequate empirical results. Lastly, allowing the volatility of errors to vary over time is becoming increasingly important in macroeconomics, not only because the volatilities of many macroeconomic variables have changed over time (e.g. going from the 1970’s to the Great Moderation in mid-80’s.), but also because many issues of macroeconomic policy hinge on error variances of, amongst other, price and output levels. For these reasons, we wish to capture these volatility variations in our model, and study the responses of monetary and fiscal policies to these shifts in the economy.

The paper makes four principal contributions. First, we observe significant time variation in the model parameters (and volatilities of residuals) between 1979 and 2012. All our results confirm that there are three regimes in the US economy: the Volcker chairmanship (1979-84), the Great Moderation (1985-2007), and the Great Recession (2008-12). More specifically, we observe significant differences in the endogenous responses to shocks in particular between the Volcker period and the Great Recession, and find that monetary policy reacts more aggressively during Volcker chairmanship and fiscal policy during the Great Recession to stabilize the economy. Second, impulse responses show that there is a high degree of interactions between monetary and fiscal policies over time. Whereas for a tax shock, the policies act as substitutes, we note significant time variation for the other shocks. On one hand,

the two policies behave as substitutes for both the monetary policy and government spending shocks during the Volcker era, while on the other, they behave as compliments during the Great Recession. Moreover, both the monetary and (net) fiscal policy has a stabilizing effect on output, albeit government spending behaves in a destabilizing fashion. Third, decomposition of forecast error variance of government spending shows that spending itself is largely acyclical, indicating strong inertias and path-dependencies in spending decisions. In addition, we find that while government revenues largely influence decisions on spending, spending does not influence tax decisions. Along the same lines, we observe a significant degree of coordination between monetary and fiscal authorities in the decomposition exercise where both authorities take into account the decisions of the other. Fourth and final, our analysis of the fiscal transmission channel reveals two things. Tax cuts, because of their crowding-in effects, are more efficient in expanding the economy than government spending rises, since the tax multiplier is higher and more persistent, in particular during the Volcker regime. The second thing we note is that fiscal shocks are more quickly transmitted onto prices than the monetary policy shock. This suggests there might be frictions in the US monetary transmission channel, such as financial market frictions (banking, credit, leverage) that cause a delayed response of prices to monetary policy shocks.

The remainder of the paper is outlined in the following way. Section 3.2 describes the econometric framework, including data, the identification scheme, the model specification, and the Bayesian technique used (further details on Bayesian inference including the sampling algorithm and the convergence diagnostics of the Markov chain are explained in Appendix I). We go on by discussing our first results from the impulse responses in section 3.3, where we also try to identify different fiscal-monetary regimes in the US. In addition, we identify and analyze the fiscal multipliers in the same section, and compare our findings to a fixed coefficient structural Bayesian VAR. In section 3.4, we establish the importance of fiscal and monetary shocks as drivers of output and the other variables in our model. Section 3.5 concludes.

## 2 Econometric Methodology

The method we use is a structural time varying vector autoregressive model (TVP-VAR) with sign restrictions estimated on quarterly US data from 1979:I to 2012:II.



We allow for variation over time in the estimated coefficients of the model and in the variance-covariance matrix of the residuals. This is a strong advantage over fixed-parameter VARs as it allows us to capture any gradual structural shifts that might occur in the economy at  $t = 1, \dots, T$ . Our results are derived from analyzing (structural) impulse response functions and forecast error variance decompositions.

The flexibility of a TVP-VAR does not come without costs. The computational burden increases rapidly with the number of endogenous variables, lags and the set of identifying restrictions. To keep the amount of parameters and restrictions manageable, we will restrict ourselves to five variables and two lags.<sup>5</sup> Moreover, we identify the shocks randomly distributed only once within three specific regimes. The first regime corresponds to the Volcker chairmanship (1979-1984); the other two somewhat loosely to the Great Moderation (1985-2006) and Great Recession (2007-2012). Although focusing on a few regimes instead of every  $t$  slightly restricts the flexibility of the time varying approach but, on the other hand, such a focus can be thought as a more elaborate subsample strategy. Primiceri (2005) has implicitly taken and defended a similar route.

## 2.1 Model Specification

The  $k$ -vector of quarterly variables  $\{y_t\}_{t=1}^T$  includes government spending, net taxes, output, inflation and a short-term interest rate in that order. We assume  $y_t = (y_{g,t}, y_{t,t}, y_{x,t}, y_{\pi,t}, y_{i,t})'$  evolves according to the TVP-VAR(p) process,

$$y_t = C_t + B_{1,t}y_{t-1} + \dots + B_{p,t}y_{t-p} + u_t, \quad (1)$$

in which  $C_t$  is a  $k \times 1$  vector of time varying intercepts,  $B_{i,t}$  ( $i = 1, \dots, p$ ) is a  $k \times k$  matrix of time varying coefficients and  $u_t$  are possibly heteroscedastic reduced-form residuals with variance-covariance matrix  $\Omega_t$ . Iterating on (1) yields the corresponding infinite moving average representation, i.e.

$$y_t = \mu_t + \sum_{h=0}^{\infty} \Theta_{h,t} u_{t-h}. \quad (2)$$

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<sup>5</sup>Primiceri (2005), and Cogley and Sargent (2005) employ a 3-variable monetary TVP-VAR. Kirchner et al. (2010), Pereira and Lopes (2011), and Hauzenberger(2012) use a 4-variable fiscal TVP-VAR. All these papers use two lags.

$\Theta_{0,t} = I_k$ , or a  $k$  dimensional identity matrix,  $\mu_t = \sum_{h=0}^{\infty} \Theta_{h,t} C_t$  and  $\Theta_{h,t} = J \tilde{B}_t^h J'$  in which  $\tilde{B}_t$  is the corresponding TVP-VAR(1) companion form of the TVP-VAR(p) in (1) and  $J$  denotes a selector matrix:<sup>6</sup>

$$\tilde{B}_t = \begin{bmatrix} B_t \\ I_{k(p-1)} : 0_{k(p-1) \times k} \end{bmatrix} \quad \text{and } J = (I_k : 0_{k \times k(p-1)}). \quad (3)$$

The parameters  $\Theta_{h,t}$  for  $h = 1, \dots, H$  represent the reduced-form impulse response functions. To transform these responses into ones with a structural interpretation we proceed in two steps. First, we decompose the reduced-form variance matrix  $\Omega_t$  in a standard triangular fashion and then, in a second step, we identify the structural shocks through sign and other restrictions on the impulse responses. Specifically,

$$u_t = A_t^{-1} \Sigma_t G_t \varepsilon_t \quad (4)$$

in which  $\varepsilon_t$  are the normalized structural shocks (i.e.  $\varepsilon_t \sim N(0, I_k)$ ),  $A_t$  is lower triangular with ones on the main diagonal;

$$A_t = \begin{bmatrix} 1 & 0 & 0 & 0 \\ a_{21,t} & 1 & 0 & 0 \\ \vdots & \ddots & \ddots & \vdots \\ a_{n1,t} & \cdots & a_{nn-1,t} & 1 \end{bmatrix} \quad (5)$$

$\Sigma_t$  is a diagonal matrix with entries  $\sigma_{i,t}$  ( $i = 1, \dots, k$ ), or a matrix of uncorrelated variances;

$$\Sigma_t = \begin{bmatrix} \sigma_{1,t} & 0 & 0 & 0 \\ 0 & \sigma_{2,t} & 0 & 0 \\ \vdots & \ddots & \ddots & \vdots \\ 0 & \cdots & 0 & \sigma_{k,t} \end{bmatrix} \quad (6)$$

and  $G_t$  is an orthonormal rotation matrix. Given the properties of  $G_t$  and  $\varepsilon_t$  we can write the decomposition of the reduced-form variance-covariance matrix as

$$\Omega_t = A_t^{-1} \Sigma_t \Sigma_t' A_t^{-1'}. \quad (7)$$

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<sup>6</sup>We will see in just a short while that  $I_K = V(\epsilon_t)$ .

This is the first step in our transformation into structural impulse responses. Therefore, combining 4 with the reduced-form impulse response function on the right-hand side of 2, the structural impulse responses follow then from:

$$\Phi_t = (\Theta'_{0,t} : \dots : \Theta'_{H,t})' A_t^{-1} \Sigma_t G_t, \quad (8)$$

in which we rotate the orthonormal matrix  $G_t$  until  $\Phi_t$  satisfies all the imposed restrictions, and the forecast error variance decomposition of  $y_t$  can be extracted from the diagonal elements of

$$\Omega(y)_{h,t} = \sum_{h=0}^H \Theta_{h,t} \Omega_t \Theta'_{h,t}. \quad (9)$$

This is the second step. We have now identified the complete structural impulse responses, including the forecast error variance decomposition. Let us continue by re-writing the TVP-VAR (p) model 1.

For the estimation it will be practical to collect the slope coefficients  $B_t = (B_{1,t} : \dots : B_{p,t})$  in a  $k \times kp$  matrix and to transform it together with the constant into a  $k(kp+1)$  vector of VAR coefficients by stacking the columns, i.e.  $\beta_t = \text{vec}(B_t : C_t)$ . The model in (1) can now be rewritten as

$$\begin{aligned} y_t &= X_t' \beta_t + A_t^{-1} \Sigma_t G_t \varepsilon_t, \\ X_t' &= (y'_{t-1} : \dots : y'_{t-p} : 1) \otimes I_k, \end{aligned} \quad (10)$$

in which the operator  $\otimes$  denotes the Kronecker product. Like the VAR coefficients, we bring the non zero and one elements of the covariances  $A_t$  and volatilities  $\Sigma_t$  into vector form:  $\alpha_t = (\alpha_{21,t}, \alpha_{31,t}, \alpha_{32,t}, \dots, \alpha_{k1,t}, \dots, \alpha_{kk-1,t})'$  and  $\sigma_t = (\sigma_{1,t}, \dots, \sigma_{k,t})'$  where the corresponding dimensions are  $k(k-1)/2$  and  $k$ . This way of decomposing the variance-covariance matrix in 10 is not unique to the TVP-VAR literature, but is also widely applied in the literature considering the problem of efficiently estimating covariance matrices.<sup>7</sup>

The vectors  $\alpha_t$ ,  $\beta_t$ , and  $\sigma_t$  summarize all the time varying parameters of the model.<sup>8</sup>We have in effect transformed the TVAP-VAR(p) expression 1 into 10. In

<sup>7</sup>See Pourahamadi (2000), or Smith and Kohn (2002).

<sup>8</sup>In Cogley (2003), and Cogley and Sargent (2005),  $\alpha$  is time invariant, meaning that an innovation in the  $i$ -th variable has a time invariant effect on the  $j$ -th variable. However, our purpose is to model time-variant simultaneous interactions of equations, which means that  $\alpha$  must be allowed to vary over time.

effect, the new strategy is to model the coefficient processes in 10. As in Primiceri (2005) we let the coefficients  $\alpha_t$  and  $\beta_t$  evolve as random walks and the standard deviation  $\sigma_t$  follows a geometric random walk:

$$\alpha_t = \alpha_{t-1} + \zeta_t \quad (11)$$

$$\beta_t = \beta_{t-1} + \nu_t, \quad (12)$$

$$\log \sigma_t = \log \sigma_{t-1} + \eta_t. \quad (13)$$

The specification for  $\sigma_t$  falls into the class of models known as stochastic volatility. While in infinite samples a random walk hits an upper or lower bound for sure, the use of finite samples makes it possible to maintain the random walk assumption. A great advantage as we do not have to estimate additional parameters, although, in principle, we could extend (11), (12) and (13) to represent more general autoregressive processes.<sup>9</sup>

The innovations  $\varepsilon_t$ ,  $\zeta_t$ ,  $\nu_t$ , and  $\eta_t$  are mutually uncorrelated Gaussian white noises with zero mean and variances defined by the identity matrix  $I_k$  and the hyperparameters  $Q$ ,  $S$  and  $W$ .<sup>10</sup> Summarized in the variance-covariance matrix  $V$  we have:

$$V = \text{Var} \left( \begin{bmatrix} \varepsilon_t \\ \nu_t \\ \zeta_t \\ \eta_t \end{bmatrix} \right) = \begin{bmatrix} I_k & 0 & 0 & 0 \\ 0 & Q & 0 & 0 \\ 0 & 0 & S & 0 \\ 0 & 0 & 0 & W \end{bmatrix}, \quad S = \begin{bmatrix} S_1 & 0 & \cdots & 0 \\ 0 & S_2 & \ddots & \vdots \\ \vdots & \ddots & \ddots & \vdots \\ 0 & \cdots & 0 & S_{k-1} \end{bmatrix}, \quad (14)$$

$S_1 = \text{Var}([\Delta\alpha_{21,t}]')$  and  $S_{i-1} = \text{Var}([\Delta\alpha_{i1,t}, \dots, \Delta\alpha_{ii-1,t}]')$  for all  $i = 3, \dots, k$ . All matrices here, besides the identity matrix  $I_k$ , are positive definite. The rather specific assumptions on the structure of  $V$  and  $S$  are standard in the literature (see, e.g., Primiceri, 2005, and Canova and Gambetti, 2009) and are not essential to keep the estimation feasible. The structure of  $V$  and  $S$  offers, however, numerous advantages: most important for our purpose is that the block diagonality of  $S$  with

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<sup>9</sup>Primiceri (2005) does extend the framework as a robustness check, and allows the coefficients and log standard errors to follow a more general AR process (varying the AR coefficients between 0.5 and 0.95). He does, however, not find any significant differences for the model performance compared to the random walk hypothesis. The only minor change is that the model captures, apart from the permanent, many temporary variations in parameters. The temporary changes are, nevertheless, irrelevant for the overall analysis.

<sup>10</sup>The priors for the model coefficients in 10 and hyperparameters are outlined and explained in Appendix II.

blocks corresponding to parameters in separate equations of the TVP-VAR enables us to model  $[\alpha_{21,t}]$ ,  $[\alpha_{31,t}, \alpha_{32,t}]$ ,  $\dots$ ,  $[\alpha_{k1,t}, \dots, \alpha_{kk-1,t}]$  in linear state space form. The advantage of linearity will become clear when we lay out the Bayesian estimation strategy for our model. Also, assuming all off-diagonal elements to be zero does not further exaggerate the curse-of-dimensionality problem (i.e. a very large number of parameters) inherent in all time varying parameter models.

## 2.2 Identification

We use sign restrictions, summarized in Table A.1, to identify jointly four orthogonal shocks: a business cycle shock which increases output and taxes; a monetary policy shock which increases the interest rate and decreases inflation and output; a spending shock which increases spending and output; and a tax shock which increases taxes and decreases output. In addition, there is a residual shock in this model.<sup>11</sup> However, because it is not identified, it does not have a structural interpretation, and therefore we do not report it. Moreover, sign restrictions are a partial identification method and there is therefore no necessity to identify as many fundamental shocks as variables in our model (see, e.g., Uhlig, 2005). All restrictions must hold for one quarter, except for the responses of the variables which are directly associated to the shock (e.g. tax shock on taxes), they must hold for two quarters. Having somewhat longer restrictions here rules out transitory effects. The signs of the restricted responses are relatively uncontroversial and consistent with most dynamic general equilibrium models and Keynesian aggregate supply and demand diagrams.<sup>12</sup>

Of course, such a strong view on the sign of the responses discards, at least on impact, more controversial phenomena such as expansionary fiscal contractions (see, e.g., Giavazzi et al., 2000) or the price puzzle. With our strong view we avoid however some issues often criticized in the structural VAR literature, for example the missing link between theory and a simple Choleski decomposition (i.e. a causal ordering of the variables) or the weak information provided by sign restrictions if one takes a too agnostic view on the identification of shocks (see, e.g., Canova and Pina, 2005, and Canova and Paustian, 2011). Being too agnostic may have especially severe consequences if the relative variance of the shock of interest delivers a weak

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<sup>11</sup>The residual shock can be viewed as innovation to inflation in  $u_t$ .

<sup>12</sup>Canova and Pappa (2007), Mountford and Uhlig (2009), and Pappa (2009) apply a similar identification scheme through sign restrictions to study the effects of fiscal policy, and Chadha et al (2010) apply a similar scheme to a monetary policy framework.

signal. The usual suspect here is the monetary policy shock. So the relatively large number of theory driven restrictions and our rich shock structure should a-priori lead to a good performance and reliability of our approach.

Although it is not of our primary interest, identifying a business cycle shock is crucial to adequately track the source behind the fiscal shocks, especially on the tax side (see, e.g., Blanchard and Perotti, 2002, and Mountford and Uhlig, 2009). In this way we can disentangle whether a change in taxes comes from fluctuations in output or a tax shock. Just as a remark, we do not differentiate between a demand driven or supply driven business cycle shock; the results will, however, provide us with an indication of the relevant driver in a particular regime.

In addition to restricting the signs we also impose magnitude restrictions. First, we narrow down the elasticity of taxes to output in the matrix of contemporaneous effects  $G'_t \Sigma_t^{-1} A_t$ . Most papers in the tradition of Blanchard and Perotti (2002) predetermine this elasticity, the one which essential separates tax and business cycle shocks, at values somewhere around (minus) 2. Hauzenberger (2012) estimates time varying elasticities over the last 45 years and finds values larger than zero but lower than 3. Accordingly, we limit the respective coefficient in the  $G'_t \Sigma_t^{-1} A_t$  matrix to that range and in the same way we restrict the spending and tax multipliers to be lower than 3 on impact. Such an upper restriction on the impact multiplier is relatively liberal and captures most of the values found in the literature (e.g., Ramey, 2011, Romer and Romer, 2012, and Favero and Giavazzi, 2012). Kilian and Murphy (2012) show how imposing plausible bounds effectively reduces the number of admissible but empirically implausible models. Second, in certain cases it is not possible to fully disentangle the four shocks by the restrictions in Table A.1. When the candidate response for a spending shock implies an increase in taxes, it could also represent a business cycle shock. Rather than discarding, and essentially imposing a negative sign on the response of taxes to a spending shock, we disentangle the two shocks through a relative magnitude restriction: a business cycle shock that increases output by one-dollar must have a larger effect on taxes in absolute terms than a one-dollar spending shock. The relative magnitude restriction must hold for two quarters.<sup>13</sup>This procedure further helps in reducing the number of implausible models (see, e.g., Duguay and Fry, 2009).

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<sup>13</sup>Two quarters is a reasonable assumption since cyclical movements have a longer lasting impact on taxes than spending. However, the results do not significantly change if the relative magnitude restriction is applied only for one quarter. In any case, this assumption is much less restrictive than the negative tax response restriction.

We have started the project with the ambitious goal of identifying jointly the four shocks in every period  $t$ . As it turned out, such a goal is computationally too demanding and we therefore opted for a different strategy, identifying the shocks only once within the three specific regimes of the Volcker chairmanship (1979-1984), the Great Moderation (1985-2006) and the Great Recession (2007-2012).<sup>14</sup>Formally, define  $S$  as the set of sign and magnitude restrictions, and let  $G_t^{(r)}$  be one orthonormal rotation matrix in (8).<sup>15</sup>Then, to find one representative impulse response for the Volcker Chairmanship,

$$\Phi_V = (\Theta'_{0,t} : \dots : \Theta'_{H,t})' A_t^{-1} \Sigma_t G_t^{(r)}, \quad (15)$$

we randomly pick a quarter  $t$  from  $T_V, T_V + 1, \dots, T_M - 1$  and rotate  $G_t^{(r)}$  over  $r = 1, 2, \dots, R$  until there is one  $r$  such that  $S \subset \Phi_V$ ; and in the same way we search for  $\Phi_M$  and  $\Phi_G$  in the Great Moderation and Great Recession with  $t \in (T_M, \dots, T_R - 1)$  and  $t \in (T_R, \dots, T)$ . The specific dates defining the three regimes are  $T_V \equiv 1979:I$ ,  $T_M \equiv 1985:I$  and  $T_R \equiv 2007:I$ . If we fail to find an admissible impulse response within the maximum number  $R$  of allowed rotations, we pick a different  $t$  and start our search again.

As a robustness check of our identification procedure we also run a recursive scheme. It will be a pseudo recursive identification, to be precise, because we keep rotating the two-by-two block of taxes and output to separate the tax and business cycle shocks. Unlike spending and monetary policy shocks, which can be identified by ordering spending first and the short-term interest rate last (see, e.g., Perotti, 2007, and Christiano et al., 2005) the other two shocks cannot be identified by a simple causal ordering. Therefore, to have a better comparison with our main identification procedure we keep the sign restrictions on the tax-output block.

## 2.3 Estimation

We estimate our TVP-VAR using Bayesian methods on quarterly data from 1979:I to 2012:II for our five variables: government spending, net taxes, output, the inflation rate and a short-term interest rate. To keep our results comparable with

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<sup>14</sup>Since our sample includes over 130 quarters, identifying all sign restrictions in each quarter is computationally very demanding and results in many unstable draws. We therefore opt for the alternative strategy outlined below, which moreover is standard in the TVP-VAR literature.

<sup>15</sup> $G_t^{(r)}$  comes from a QR decomposition of a  $k \times k$  standard normal matrix with the upper triangular part normalized to be positive.

Blanchard and Perotti (2002) and other studies in their tradition, we define the fiscal variables in the same way: government spending includes both government consumption expenditures and gross investment, and net taxes are the current receipts less net transfers and net interest paid. Note that these are not expressed as ratios to GDP, but directly in levels (in order to facilitate the interpretation of these variables to the various shocks). On the nominal side we measure inflation as the quarterly change of the output deflator and use the 3-month T-bill rate as our short-term interest variable; both are expressed in percent per quarter.<sup>16</sup>The three variables on the real side of the economy enter the TVP-VAR as the logarithm of their real, per-capita values.<sup>17</sup>The TVP-VAR is estimated in levels.<sup>18</sup>

Since we do not have a closed form solution for the posterior distribution of the structural parameters we use a Markov chain Monte Carlo (MCMC) algorithm for the numerical evaluation. Taking the Bayesian route together with somewhat informative priors effectively deals with the large dimensionality of the TVP-VAR compared to maximum likelihood techniques where it is hard to rule out peaks in the likelihood in uninteresting regions of the parameter space. Estimation further exploits the fact that it is typically easier to draw from a lower dimensional distribution, conditional on a set of parameters. Specifically, conditional sampling requires to treat the VAR coefficients  $\beta_t$ , the covariances  $\alpha_t$  and the volatilities  $\sigma_t$  as separate blocks in a Gibbs sampler.<sup>19</sup> Appendix B has a detailed exposition of our prior choice and the sampling strategy.

The Gibbs sampler does not ensure that every single  $\beta_t$  from a draw of the sequence  $\{\beta_t\}_{t=1}^T$  leads to a stable VAR representation. Cogley and Sargent (2005) discard a draw as soon as they find a  $\beta_t$  with eigenvalues larger than one in modulus. Such a strict rule may not be practical here for two reasons: one is policy related

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<sup>16</sup>Using the Federal Funds rate instead of the T-bill does not change the results.

<sup>17</sup>The data sources are the National Income and Product Accounts (NIPA) from the Bureau of Economic Analysis (BEA) and the Federal Reserve Economic Data (FRED). Specifically, NIPA tables 1.1.4 (line 1), 1.1.5 (lines 1 and 21), 3.1 (lines 1, 9, 11, 15 and 22), 7.1 (line 18), and FRED series TB3MS for the 3-month T-bill rate. All variables were downloaded on September 1, 2012.

<sup>18</sup>Mixing the I(0) and I(1) data for the Bayesian TVP-VAR estimation is not unusual in the literature and has been applied by, amongst others, Kirchner et al (2010), and Nakajima (2011). Another example is Christian et al (2005) who estimate their New-Keynesian model using Bayesian methods and a mix of I(0) and I(1) data. We deal with it by imposing a mild stability condition on the first differences. Specifically, we check the roots of the associated VECM polynomial of the VAR and discard every draw that has more than  $k = 4$  roots in or on the unit circle. See Hauzenberger (2012) for more details on this transformation of the level TVP-VAR( $p$ ) in 1 and for checking the roots.

<sup>19</sup>Gelman et al. (1995, Chap. 11) show that the stationary distribution of the Markov Chain generated by the Gibbs sampler is the joint distribution one is looking for.



and the other one is of statistical nature. Unlike monetary policy the objective of fiscal policy does not necessarily lie in stabilization, and the use of spending, taxes and output in levels basically rules out stability. It is therefore more practical to impose a relatively weak condition on a quasi differenced version of the model in which we transform the autoregressive coefficients in the spending, tax and output equations to represent a specification in first differences.<sup>20</sup>

After a burn-in period of 50,000 iterations we start saving every third draw from the joint posterior distribution until a total of 20,000. The “thinning” helps to break the autocorrelation of successive draws; Appendix B.3 provides satisfactory convergence diagnostics of the MCMC chains. All of the 20,000 saved draws must satisfy the sign, magnitude and stability restrictions. Specifically, for each of the 20,000 draws we randomly pick a quarter from the Volcker period, the Great Moderation and the Great Recession and generate the impulse responses from (15). As a result, we get three distributions of impulse responses that are representative for the effects, interactions and the transmission of fiscal and monetary policy in our three episodes. In the discussion we will focus on the median as a summary measure. The median is not uncontroversial: Fry and Pagan (2007) criticize the lost orthogonality property of the shocks when the summary measure mixes different draws of admissible models. Their remedy to restore orthogonality suggests to use the single model that comes closest to the median. Canova and Paustian (2011) dig a little deeper into the issue and find the median to be an acceptable summary measure, performing reasonably well compared to Fry and Pagan’s (2007) close-to-median rule.

### 3 Fiscal and Monetary Interactions

We organize the discussion of the results in the following way. Section 3.1 discusses the time variant volatility pattern of the estimated model coefficients. We continue by analyzing the endogenous responses to business cycle, government spending, tax and monetary policy shocks. A business cycle shock is defined as a shock that jointly moves output and taxes in the same direction. This is an important assumption because when output and taxes move in the same direction, we essentially assume that this must be due to some improvement (deterioration) in the business cycle generating the increase (fall) in taxes, not the other way around. Moreover, the

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<sup>20</sup>See Hauzenberger (2012) for more details about imposing a weak stability rule on variables in levels with an obvious trend.

effect of the business cycle shock on taxes (in absolute terms) must be larger than the effect of a spending shock for two consecutive quarters following the shock. Identifying a business cycle shock is crucial to adequately track the source behind the fiscal shocks, especially on the tax side (see, e.g., Blanchard and Perotti, 2002, and Mountford and Uhlig, 2009). In this way we can differentiate between automatic stabilizers and active policy decisions.<sup>21</sup>In addition, there is a fifth shock in this model, a residual shock. However, because it is not identified, it does not have a structural interpretation, and therefore we do not report it. Moreover, the sign restrictions are a partial identification method and there is therefore no necessity to identify as many fundamental shocks as variables in our model (see, e.g., Uhlig, 2005).

Our main interest is in detecting possible structural shifts in the economy, as well as shifts in the application of both monetary and fiscal policy. In addition, we hope to find sufficient evidence to determine when and whether the three policies (monetary, spending, and tax) have stabilizing or destabilizing effects on output. We compare our findings with the key results in the literature.

However, before we begin the discussion, we would also like to introduce some key concepts that we will be making use of throughout the subsequent sections. The first one refers to interaction and coordination of the two policies. Following the large literature on policy interactions, if the two policies exhibit a positive or negative correlation (or a common cyclical pattern) implying that one policy responds strategically to the actions of the other (in whatever direction), we say that the two policies interact, or coordinate their responses. Going one level deeper and following Muscatelli et al (2004), if the interaction has a positive correlation, we define the two policies as being compliments. In contrast, if the two policies have a negative correlation, then the two policies act as substitutes. Finally, the last level of policy analysis regards the responses of the two policies to innovations in output, as in Melitz (2002) and Muscatelli et al (2004). If the interest rate rises after a business cycle shock, we say that the monetary policy acts in a stabilizing fashion. Likewise, if taxes rise, or government spending falls following the same business cycle shock, we equally say that the fiscal policy acts to stabilize output. Since we superimpose via our identification scheme that taxes will always rise following a positive business cycle shock, the final outcome on the fiscal side will therefore depend on the sign

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<sup>21</sup>While we only consider the movements in total government revenues, and not in the marginal tax rate textitper se, Baxter and King (1993) show that since the end of the war (1944-45), the two have moved tightly together and thus can be viewed as the same thing.

and the magnitude of responses of government spending.

### 3.1 Time Variant Volatility Patterns

Looking at Figure II.1, we can identify at least two periods of exceptionally high volatility in the residuals of the TVP-VAR equations. The first one is at the beginning of our sample period (1979-1984) which falls under the early Volcker period (in line with the findings of Primiceri, 2005), when the interest rate and inflation experienced their highest peak, as well as output and spending.<sup>22</sup>The second period is during the Great Recession (2007-2012), when the volatility of taxes increased, and that of output and spending to a certain extent. In the two decades preceding it, the volatility of the two variables was maintained at a constant level. We should therefore expect to see more volatility in impulse responses during those two periods compared to the Great Moderation (1985-2006). This is interpreted as a first indication that there are these three regimes in our data.

### 3.2 Impulse Response Analysis

The impulse responses are reported for the three distinct periods in Figures II.2 to II.5. The blue line with circles corresponds to the median response during the Volcker era (1979-1984). The second represents the median response during the Great Moderation (1985-2006), while the third is the median impulse response during the Great Recession (2007-2012). We initially performed a fully flexible and time-variant scheme, allowing the shocks to be identified in every quarter, but detected that most time-variation occurred between the three regimes. Since minimal variation was observed within those three regimes, and in order to keep our discussions focused, we follow the approach by Primiceri (2005) and Kirchner et al. (2010), and in the same figure report the representative (i.e. median) response for each regime.

The reader will notice that some impulse responses are reported in terms of “percent or percentage deviations from trend”, while others are reported in terms of “dollar deviations from trend”. The responses of output, spending and taxes to a business cycle, spending and tax shock are therefore reported in terms of (non-cumulative) multipliers (see Blanchard and Perotti, 2002, and Kirchner et al., 2010).

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<sup>22</sup>Since output and spending are specified in levels in the estimations, we observe the increase in volatility as an increase in level. Another possibility would have been to express the two variables in quarterly growth rates, just as the interest rate and inflation, whereby we would observe a similar peak in the former like we observe in the latter two.

In other words, we convert the initial estimates of the variables we use in log-levels output, spending and taxes from elasticities into derivatives by multiplying it with the prevailing ratio of the responding and shocked variables. For the spending multiplier we can write this conversion as (the same conversion applies to the remaining two variables):

$$\frac{\Delta Y_{t+h}}{\Delta G_{t+h}} = \frac{Y_t}{G_t} \frac{\partial \log Y_{t+h}}{\partial \log G_{t+h}}, \quad h = 0, 1, \dots, H \quad (16)$$

in which  $Y_t$  and  $G_t$  are the levels of output and spending,  $H$  defines the impulse response horizon, and the log-derivatives follow from (8). The prevailing ratio ( $\frac{Y_t}{G_t}$  in this case) is independently calculated for each regime by randomly selecting a quarter within a regime (Volcker Chairmanship, Great moderation, and Great Recession separately). Once a quarter in each regime which satisfies all the sign restrictions has been located, the ratio is calculated based on the values obtained in that quarter. Thus, the ratio is also time varying. The size of all shocks are normalized and represent, depending on the units of the shocked and the response variable, either a one dollar, percent or percentage point innovation.

The first thing to note is that there is significant time variation in the impulse responses. The magnitudes in the responses differ considerably between the regimes. Moreover, for government spending and monetary policy shocks, we observe a qualitative difference in responses besides the quantitative. This confirms our selection of the three regimes (or economic structures) in our sample. This is in stark contrast to the findings of Cogley and Sargent (2005), Primiceri (2005), and Koop and Korobilis (2009) who find the majority of the time variation in the variance of the residuals, but not in the TVP-VAR coefficients.<sup>23</sup> We believe that the disparity in our results reflect the fact that we have included fiscal variables and shocks in our model, thereby studying much richer dynamics. This explanation is supported by the findings of Rossi and Zubairy (2011) described in the introduction. Also, Kirchner et al. (2010) and Pereira and Lopes (2010) find significantly higher time variation in the impulse responses in their fiscal TVP-VAR compared to a monetary one.

Second, we observe minor differences between our sign-restriction approach and the recursive. In most cases, there are only minor differences in magnitudes of the responses, but qualitatively they are the same. The only exception is the monetary policy shock, where we observe some differences between the two methods. There

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<sup>23</sup>More recently, Kim and Yamamoto (2012) have found statistically significant evidence of time varying coefficients in a simple monetary model.

are two reasons for that. The first is related to the weak impact of the monetary policy shock. The literature on sign restrictions has found that without imposing the restrictions on some of the variables in the model, the impact of the shock is marginal. Therefore in order to generate the impact in line with the theoretical literature, you need to impose plenty of sign restrictions on the model (Canova and Paustian, 2011). In our case, we impose restrictions on three variables: output, inflation, and the interest rate. This is of course absent in the recursive approach. The second is related to the fact that in the recursive approach, the interest rate is ordered last in the model, resulting in a lag on the impact of the monetary policy shock on the remaining variables. This is, however, inconsistent with the theoretical literature, which finds an immediate impact of monetary policy on the economy. In this sense, our framework is more appropriate since we observe contemporaneous effects of the monetary policy.

To summarize, our method comparison shows that our identification scheme is consistent and robust. For most shocks, we only observe some minor differences in the magnitudes of the impulse responses, which, taking into account that our shocks are well identified, means that our results are reliable. Further, the advantages derived from applying sign restrictions for a monetary policy shock indicate that our method is preferred to the recursive. Let us now have a more detailed look at each shock.

### 3.2.1 Business Cycle Shock

Figure 5 reports the impulse responses of each variable to a business cycle shock. We do not *ex ante* differentiate between demand-side and supply-side business cycle shocks. The responses of output, spending and taxes are expressed as dollar for dollar (or level responses). Interest rate and inflation, on the other hand, are reported in the standard form of percentage point changes. Recall that inflation and the interest rate are expressed in quarterly growth rates. To get them into annual growth rates, the impulse responses of those two variables should be multiplied by 4.

We observe significant variation in impulse responses over the three regimes. Following an expansion in output, the interest rate is more responsive during the Volcker period. The interest rate responds by 5 basis points (or 20 in annualized terms) more compared to the Great Moderation, or 10 basis points (or 40 in annualized terms) more than during the Great Recession, resulting in a lower inflation.

Hence, we also observe the more expansionary monetary policy during the most recent episode in our results. The fiscal policy is in relative terms more expansionary during the Volcker era. While spending rises by more than in the two other periods, taxes rise by, on average, 0.1 dollar less. The business cycle shock is also very persistent, and the responses of output continue to rise 3 quarters after the initial shock in all three regimes.

As Muscatelli et al. (2004), we observe a complementarity between monetary and fiscal policies. In all three regimes, the monetary policy is tightened as a response to an expansion in output, and in parallel the fiscal policy is tightened, via higher taxes.<sup>24</sup> Spending also increases, but the increase in taxes is much higher, hence the overall impact is a tighter fiscal policy. Moreover, both the monetary and the fiscal side react in a stabilizing way to contemporaneous output. However, as Melitz (2002) we find that government spending (contrary to taxes) reacts in a destabilizing fashion to innovations in output. Net stabilization of the fiscal side therefore only occurs because of a larger reaction of taxes than expenditures.<sup>25</sup>

### 3.2.2 Government Spending Shock

We wish to examine two things in this section. First, we wish to establish possible structural shifts in the economy, and whether the government spending shock changes over time. Second, we wish to understand the degree of policy interactions under a government spending shock. The responses of output, government spending and taxes are reported as dollar (or level) responses to a one-dollar spending shock.

As guidance in interpreting our results in Figure 5, we use the findings from Rossi and Zubairy (2011) on the effects of a government spending shock in a time-invariant VAR framework. They find that an increase in government spending leads to a minor increase in output (by approximately 20 percent of the size of the initial shock), a fall in interest rate, and a fall in the inflation rate. Our time varying exercise suggests that the expansion is similar, by between 1 and 1.25 dollars to a one dollar increase in spending for much of the sample period. Taxes also rise to finance the increase in public spending, but by less than the initial increase in

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<sup>24</sup>The relative magnitude restriction may partially be responsible for this response. Nevertheless, since we do not impose a restriction on the reaction of spending, nor a full restriction on magnitude restriction on taxes, we largely allow the data to guide us in the interpretation.

<sup>25</sup>The magnitude restriction on taxes following a business cycle shock is very broad, which means that the magnitude of tax response to an innovation in output has been fully data driven. Therefore the final result we get for the fiscal side can be seen as empirically driven.

public spending. In contrast to Rossi and Zubairy (2011), our inflation rate increases marginally, by between 0.01 and 0.05 percentage points (0.04 to 0.1 in annualized terms), which triggers a reaction of the monetary authority. They increase the rate by approximately 0 to 0.01 percentage points (0 to 0.04 in annualized terms) for most of the sample period. During the Volcker period, however, the response was stronger, with a rise of up to 0.035 percentage points (or 0.14 in annualized terms). As a result of the stronger monetary policy reaction during the Volcker era, the inflation was slightly negative, despite the initial expansion on the fiscal side. On the other hand, the relative laissez-faire attitude of the latest regime results in the highest inflation rate for the entire sample period.

One explanation for the slight expansionary monetary policy during the Great Recession is that because spending policy is less effective during this period, the monetary policy needs to provide the initial stimulus in order to sustain the impact of the fiscal expansion, and prevent a more drastic fall of output to trend. Hence, both the fiscal and monetary policies were coordinating their actions in order to prevent a rapid contraction in output.

Turning to the nature of policy interactions, we observe two things. During the Volcker period and the Great Moderation, the monetary policy and government spending act initially as substitutes, meaning that when government spending increases, the interest rate is increased. 3 quarters after the initial shock, the interest rate starts to fall, while spending decreases. On the other hand, during the Great Recession, the two policies have acted as compliments. A fiscal expansion has been accompanied by a monetary policy expansion.

### **3.2.3 Tax Shock**

Let us next examine a positive one-dollar tax shock. Similar to the government spending shock, we wish to both uncover structural shifts as well as examine the level of policy interactions during our sample period. Figure 5 reports the relevant impulse responses. The responses of output, government spending and taxes are expressed as dollar for dollar (or level responses). Interest rate and inflation, on the other hand, are reported in the standard form of percentage point changes.

To guide the interpretation of our results, we will contrast our findings to Mountford and Uhlig (2009), which in many aspects is similar to our framework. In response to a 2 percent tax increase which lasts for a year after the initial shock, they find that output decreases by 0.6 percent 11 quarters out, government spending falls

by 0.7 percent after 7 quarters, while (counter-intuitively authors admit) price levels increase by up to 0.3 percent until quarter 10, and the interest rate rises by around 0.3 percentage points before it start falling after 7 quarters.. Our findings are strikingly similar to Mountford and Uhlig (2009). For most of the sample period, the decrease in taxes leads to an rise in output between 0.9 and 1.3 dollars. Spending also rises by up to 0.2 dollars. Analogous to Mountford and Uhlig (2009), inflation goes down by between 0.02 and 0.025 percentage points.<sup>26</sup>The interest rate initially rises by 0.01 percentage points (0.04 in annualized terms), but starts falling immediately thereafter to  $-0.02$  percentage points ( $-0.08$  percent in annualized terms) in order to correct for the falling inflation. Since these responses are similar to the endogenous responses to a positive technology shock in a standard New-Keynesian model, this suggest that a tax reduction improves the supply side efficiency in production, possibly via a lower tax-burden on profits, leading to higher re-investment, and lower production costs. In all regimes, we observe a very persistent response of output to a negative tax shock, even in the medium-run (or 20 quarters after the shock).

Nevertheless, we see significant variations in the medium/long-run responses between the three regimes. Whereas the impact response of output is between 0.9 and 1 in all three periods, 5 quarters after the initial shock, they deviate remarkably. During the Great Recession, the medium-run response of output is persistent, but only 1.2 dollars. For the Great Moderation, it is 1.4 dollars, while for the Volcker period, it is considerably higher at 1.8 dollars. At the same time, the impact on spending is the least during the Volcker period, with an increase of only 0.1 dollars, while it is twice as high during the Great Recession. Taking into account that the fall in inflation was the highest during Volcker period, of 0.025 percentage points (0.1 percent in annualized terms), and lowest during the Great Recession, this implies that the tax reforms, would have been the most efficient during the Volcker regime, and in relative terms the least efficient during the most recent recession. Our first results point in the direction that the tax cuts, for one reason or another do not have the same strong impact if implemented today. We will explore this point in more detail below when we discuss the multipliers.

Looking into policy coordination, the two policies behave as substitutes. Contrary to all the other shocks, however, both fiscal policies are substitutes to the monetary policy. An initial fall in taxes is accompanied by a rise in spending, which

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<sup>26</sup>Or 0.08 and 0.1 percent in annualized terms.



leads the monetary authority to increase the interest rate. As soon as the expansionary fiscal policy reverts, and taxes start to rise and spending to fall, the monetary policy is loosened, and 1 year after the initial shock, it turns below its trend.

### 3.2.4 Monetary Policy Shock

To conclude our impulse response section, let us analyze the responses to a positive monetary shock. Figure 5 reports the results. In a time invariant VAR model with both fiscal and monetary variables, Rossi and Zubairy (2011) find that a positive monetary shock leads to a contraction in output of almost the same magnitude as the initial shock, a rise in government spending of less than 10 percent of the initial shock, and initially a rise in inflation, but then after 4 quarters a fall (indicating a transmission friction to prices). While our results point in the same direction, there are some differences. The contraction in output is significantly smaller at around 0.05 dollars for a 1 percent rise in the interest rate. Similarly, government spending falls in our responses, while they rise in the case of Rossi and Zubairy (2011). Lastly, the transmission friction does not appear in our results since the inflation is very responsive to the interest rate rise, and falls immediately.

Nevertheless, we observe considerable time variation in the responses. During the Volcker period, the fiscal side does (almost) not react to the contractionary effects of the interest rate rise, resulting in a much longer recovery of output than in the other regimes. This is in line with the change in policy of the Fed in 1982, from targeting M1 to implicit inflation targeting, when their priority was to bring the inflation under control, which they succeeded better than in any other regime, from our impulse responses.

On the other end, we have the most recent regime. The rise in interest rate is followed by a contractionary (but very active) fiscal policy, since the fall in government spending is higher than the fall in taxes (the similar is true for the Great Moderation). The result is a stronger reduction on the demand side, leading to a more enhanced fall in output, and inflation compared to the other two regimes. The fall in inflation during the Great Recession is almost twice the fall of the Great Moderation, or 4 times the fall of the Volcker period. Nonetheless, the monetary authorities revert their decision after the third quarter, and the interest rates start to sharply fall, ending at (negative) 0.75 percentage points (or 3 in annualized terms) below the trend. The consequence is that output recovers more quickly from the initial contraction in Great Recession compared to the previous regimes.

Regarding the nature of interactions between monetary and fiscal authorities, we observe differences over time. While for the Great Moderation, and (to a smaller extent) the Great Recession, a contractionary monetary policy is followed by a net contractionary fiscal policy (fall in spending is higher than the fall in taxes), during the Volcker period, we observe the opposite. Hence, the two policies are substitutes during the Volcker regime, while they became compliments ever since. Muscatelli et al. (2004) find the two policies to be compliments under a monetary shock.

### **3.3 The Fiscal Multipliers**

The second thing we wish to examine in the paper is the fiscal transmission channel. One of the advantages with our framework is that we are able to disentangle monetary policy from our fiscal policy, which permits us to study the impact of fiscal spending on economic cycles. In addition, we allow for the fiscal transmission channel to vary over time. Finally, we separate the government spending multiplier from its' tax counterpart.

#### **3.3.1 The (Government) Spending Multiplier**

Figure 5 depicts the (government) spending multiplier for the 1979:I-2012:II period. Because the impulse responses of output, government spending and taxes are already reported as dollar (or level) responses to a one-dollar government spending shock, we can directly interpret the response of output as the (non-cumulative) spending multiplier.

2 periods after the initial one-dollar spending shock, we find the (peak) multiplier to reach 1.25 dollars. These results are identical to Rotemberg and Woodford (1992), who for the postwar period find the multiplier to be 1.25. Blanchard and Perotti (2002) find very similar values in their SVAR analysis with spending ordered first. Cavallo (2005), Eichenbaum and Fisher (2005), Perotti (2007), and Pereira and Lopes (2010) find it to be above 1. The slight difference with the latter might be due to the fact that we include both fiscal and monetary variables in our analysis.

Following the one dollar spending increase, taxes rise to under 0.2 dollars for 2 periods, but start sharply falling thereafter. In a theoretical model of Baxter and King (1993), Smets and Wouters (2007), or Davig and Leeper (2010) government spending can significantly crowd out the private spending and investment if higher taxes are expected in the future, in particular income taxes, which on the demand

side create strong negative wealth effects, and on the supply side induce less private capital investments and lower labor inputs. In such instances, output can even fall in response to higher government purchases. However, since taxes in our sample only marginally rise at the beginning and sharply fall thereafter, the crowding out is small (or negligible), and therefore we see a spending multiplier closer to the Keynesian ones, as in Romer and Bernstein (2009).

However, the largest difference in time lies in the medium-term impact of the multiplier. Whereas in the Great Recession and Great Moderation, the fiscal multiplier decays after 2 quarters, and the spending effects are neutralized after 10 to 12 quarters, during the Volcker regime, the multiplier is much more persistent. 20 quarters after the initial shock, the multiplier is around 0.7, implying a long-lasting impact of government spending in the early 1980's. In terms of the model outcomes of Baxter and King (1993), this would imply that the government purchase program in early 1980's was permanent and/or investment (rather than purchase) oriented. They find that permanent changes in government spending are associated with larger and longer-lasting output effects because of higher long-run labor input on the steady-state capital stock, and that permanent increases in public investment induce long-run increases in private consumption and investment, since the marginal product schedules for private labor and capital change over time (stimulating increases in labor input and private capital).

To sum up, the US impact multiplier has overall lied somewhere between 1.1 and 1.25 dollars, decaying 2 quarters after the initial spending increase. Our results are very similar to the findings of Rotemberg and Woodford (1992) and Blanchard and Perotti (2002), and also in line with Perotti (2007) and Pereira and Lopes (2010), who find the multiplier to be above one. One reason for why we find a high multiplier in our data is the very small crowding out effects of future taxes on private consumption and investment, which indicates that our multiplier is closer to the Keynesian estimates. During the Volcker regime, however, the multiplier was much more persistent, and even 20 quarters after the spending shock, the multiplier was around 0.7. This means that the government spending in early 1980's was long-run- and/or investment-oriented.

### **3.3.2 The Tax Multiplier**

Figure 5 depicts the (non-cumulative) tax multiplier for the 1979:I-2012:II period. Just as before, the impulse responses of output, government spending and taxes are

reported as dollar for dollar (or level) responses to a tax shock, meaning that we can directly interpret the response of output as the (non-cumulative) tax multiplier.

For all three regimes, the impact multiplier is between 0.9 and 1 dollar, with the lower end appearing during the most recent crises. This is significantly lower than the Romer and Romer (2010) tax multiplier, who find as high value as 3, but Favero and Giavazzi (2012) show that when you perform the same analysis in a multivariate framework, the tax multiplier becomes considerably lower.

However, a closer look at the delayed multiplier reveals a much richer dynamics. While for all periods, the multiplier is persistent and rises, the magnitudes are considerably different. In particular, during the Volcker period, the delayed multiplier reaches 1.8 dollars 4 years after the initial shock. On the other end, the multiplier rises to ‘just’ 1.2 dollars 4 years after the initial shock during the Great Recession. Therefore we conclude that the efficiency of the tax policy varies significantly over time. Nevertheless, the tax multiplier is more persistent than the spending multiplier, and does not only have significant immediate impact, but its medium-term effects are far-reaching. These results match the conclusions made by Mountford and Uhlig (2009). Using a range of policy-based scenario studies, they find that the deficit-financed tax cuts are most efficient in expanding the economy, with a maximal present value multiplier of 5 dollars of total additional output per each dollar of the total cut in government revenue 5 years after the shock.

One reason for why we find the tax cuts to be more efficient can be the crowding-in effects that such a policy creates. Cuts in taxes, in particular income taxes, result in higher private consumption and investment, independent of the purchase policy that the government pursues. This is because there is a ‘supply-side multiplier’ at work, by which decreases in tax rates rise the labor input, resulting in a n increase in output, which in turn relaxes the tax burden on private agents in the subsequent period. The velocity of the ‘supply-side multiplier’ will depend on the labor-supply and tax elasticity (Baxter and King, 1993).

In terms of the medium/long-run multipliers (spending and taxes) during recessions (with respect to expansions), we do not get a clear pattern. While we only identify the multiplier once within every regime, we can still contrast the Great Moderation as a regime with a mainly expansionary economy to the mainly recessionary of the Volcker Chairmanship, and the Great Recession.<sup>27</sup>We find that

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<sup>27</sup>We do not have a clear-cut multiplier in recessions versus expansions, since each regime identified in the paper contains periods of expansions and recessions. Nevertheless the Volcker chair-

whereas both multiplier have been the highest during the Volcker chairmanship, they have been the lowest over the Great Recession.<sup>28</sup> Since both multipliers show the same difference over time and taking into account that during the latest recession, the policy rate has been at its zero lower-bound for most of the regime, it might mean that the efficiency of the current government policies has been reduced since private agents might expect that the reversal of government might occur very soon (Corsetti et al, 2010).<sup>29</sup> Alternatively, the government expansion (and subsequent government contraction to finance it) is not perceived as temporary and therefore is expected to remain after the interest rate rise (Woodford, 2010), or because the economy is in a liquidity trap which means that the private agents believe that the economy is in a worse state than it really is (Mertens and Ravn, 2010).<sup>30</sup> Another possible explanation for the relatively lower fiscal multiplier during the Great Recession might be structural. Since the structure of the economy has shifted since the Volcker chairmanship, the government purchase and tax-reduction programs which were effective then might be, in relative terms, less effective today since they cause higher crowding-out effects, or the current fundamental problems are financial rather than demand/supply-side which implies that government spending increases/tax reductions have a smaller biting effect on the economy. Note, however, that this observation is simply in relative terms between the three regimes, which suggests that tax reductions are more effective in expanding output than spending increases still holds.

### 3.4 The Time Invariant Model

The dashed lines superimposed in Figures 5 to 5 represents the time invariant estimates for each shock, i.e. the median impulse response over the entire sample period. They are calculated using a fixed parameters structural Bayesian VAR (BVAR), where the coefficients  $\beta_t$  and the volatility  $A_t^{-1}\Sigma_t G_t$  in 10 are time-invariant. Tak-

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manship (1979-1984) and the Great Recession (200t-2012) can be considered regimes of recession, since a large share of that regime was characterized by recessions, while the Great Moderation can be considered as mainly an expansionary regime. This division is however, only indicative.

<sup>28</sup>Drautzburg and Uhlig (2011) go as far as finding a negative long-run multiplier (-0.42) from the American Recovery and Reinvestment Act of 2009.

<sup>29</sup>Since the size of the expansionary package in 2009/10 has been so high, the private agents expect a much higher reduction in spending, or increases in taxes very soon, which means that the initial effects of fiscal expansion are reduced, since agents anticipate this.

<sup>30</sup>There is however no consensus in the theoretical and empirical literature regarding the efficacy of the fiscal stimulus under a zero-lower bound. For a good overview of the debate, please see Auerbach et al (2010).

ing into account the issue of high dimensionality in parameter estimation in the time-varying VAR, with this exercise we wish to contrast whether a fixed-coefficient BVAR (that does not have issues of high-dimensionality) qualitatively and quantitatively produces similar results to a TVP-VAR, and can therefore be used as a good substitute. For this reason, we will concentrate the discussion only on the discrepancy of these results to the time-varying version.

The first thing is that we omit a lot of intertemporal dynamics by considering the time-invariant impulse response. It will either represent the median of the three periods, or over represent one regime at the expense of the other. Let us expand on this point in further detail.

In a time-invariant version, the (government) spending multipliers would be underestimated compared to a time-varying one. Similarly, the tax multiplier would be overestimated for the Great Moderation and the Great Recession, while it would be underestimated for the Volcker period. This means that the effectiveness of a tax reduction on output would be ranked lower in a time invariant model.

On policy interactions, we note a similar divergence in results. Whereas we conclude that for a government spending shock, the fiscal and monetary policies act as substitutes during the Volcker and the Great Moderation regimes, we find that they act as compliments during the Great Recession. By simply running a time invariant version, we would conclude that the two policies behave as substitutes, omitting thus the richer dynamics over time. Likewise, from a time-invariant model, we would deduce that the two policies behave as compliments, if anything. However, introducing time dynamics leads us to conclude that while the complementarity of the two policies holds for the Great Moderation and the Great Recession, it is the opposite for the Volcker period. Finally, though qualitatively the nature of policy interactions is the same for the time variant and time invariant models, the results from the time invariant one would lead us to overestimate somewhat the degree of substitution.

To conclude, the discussion has showed that a lot of time-varying dynamics in the economy is omitted if the time-invariant model is considered. While estimating a fixed-coefficient BVAR takes shorter-time, it is nevertheless a bad substitute to the time-varying version, since it drops out a lot of quantitative and qualitative information.

## 4 Forecast Error Variance Decomposition of the US Economy

To understand the fundamental forces that explain the fluctuations in the US economy, we perform a variance decomposition exercise. Just as for the impulse responses, we allow the economic structure to vary over time, thus allowing for alternating dynamics in the composition of shocks that drive the variances. The decompositions are calculated for each regime in the sample, as well as for horizons 1, 4, 8, and 20 quarters (representing the short-term and medium-term impact of shocks). As Rossi and Zubairy (2011) point out, the drivers of the variance in the short-run might be different from the medium-run, hence why we consider different horizons. We decompose our variables into four shocks: Business cycle, spending, taxes and monetary policy. Table 1 report the corresponding decompositions. As a robustness check, we have also included the variance decomposition using the recursive method in Table 2. Since we get the same results for both methods, we conclude that results based on the sign restrictions is robust, and concentrate our discussions on them, without further reference on the recursive method.

### 4.1 Decomposition on the Real Side

The fiscal shocks, tax and spending, are the strongest short and medium-term drivers of US output. Together they account for between 60 and 70 percent of the variation in output for all horizons. Reconnecting with our previous discussion that the tax shock behaves similarly to a technology shock and spending shock as a demand side shock, then it is not surprising that they explain the majority of the movement in output. Moreover, because we do not differentiate between a supply-side and demand-side business cycle shock, it is possible that the effects of both are canceling out, hence why the business cycle shock only explains 10 to 12 percent of the variation. We do not note any significant differences in the shock contributions over time for output.

Turning to public spending, not surprisingly, the government spending shock is the strongest driver of spending for all 3 regimes, and all horizons. The government spending shock explains between 40 and 50 percent of the spending volatility, depending on the horizon that we consider. The tax shock is the second most important during the Volcker period, and the Great Recession, while monetary policy

is during the Great Moderation. A possible reason for this difference is that the stability of monetary policy during the Great Moderation allowed the government to borrow more than usual since the interest rate risk was almost inexistent, and the government did not have to worry about strongly fluctuating borrowing costs. This does not, however, hold for the Volcker regime and the Great Recession, since the short-term interest rate changed dramatically, and the risks in government borrowing were much higher. Lastly, the minor importance of the business cycle shock in explaining spending variation can be interpreted as the existence of inertias and path-dependencies in the government spending decisions, implying that they are not primarily cycle driven.

Continuing with taxes, the general pattern is, not entirely shocking, that the tax shock is the strongest driver of the variance in taxes, followed by monetary policy, spending and finally business cycle shock. The strong importance of monetary policy for taxes can be interpreted as tax authorities taking into account the central bank decisions when taking their decision on tax policies.

Over the medium run, specifically at horizon 20, the shock contributions alter slightly, and spending becomes the second most important driver of taxes.

Strikingly, we find that the government spending shock explains less of the variation in taxes, than the tax shock does for the variation in spending. This indicates that government spending decisions are made taking into account the government revenue side, but tax decisions are taken independently of spending. Since we observe a rise in the importance of the government spending shock in the variation of taxes over the medium term, this might also indicate that there is a time lag between tax and spending decisions, and hence there is a delayed effect of government spending decisions on taxes (Pereira, 2008). In any case, taxes seem to play a more important role for decisions on government spending than the other way around.

## 4.2 Decomposition on the Nominal Side

The fundamental drivers of inflation are the same for the three regimes. Business cycle shock is the most important driver. However, for the subsequent ones, there is more variation over horizons. Whereas in the short-run (horizon 1), tax shocks is the most important in explaining inflation movements (15 to 19 percent), for the medium-run (horizons 4, 8, and 20), government spending shock becomes more significant, explaining around 18 percent of the inflation movement, while the signif-



importance of the tax shock decreases.<sup>31</sup> Further, the importance of the monetary policy shock rises as we increase the horizons, meaning that the lagged impact on prices is stronger than the contemporaneous one. This implies that the effects of fiscal policy on prices is quicker than that of monetary policy, which highlights the frictions in the monetary pass-through.

To conclude, let us analyze the shock composition of the interest rate variance over time. The business cycle shock is the most significant driver, followed by the fiscal variables, taxes and spending. This indicates that the interest rate movements are mainly cycle driven, which is in line with Gerba (2012), who finds that the T-bill rate is highly procyclical, with a correlation to output of 0.98. The relatively high importance of fiscal shocks in explaining interest rate movements points again towards policy interactions between the two authorities, since the central bank considers fiscal decisions when deciding on the interest rate target.<sup>32</sup>

Perhaps the most surprising is that the monetary policy shock explains the least movements in the interest rate. However, our findings are in line with Uhlig (2005), who interprets the monetary policy shock as accidental errors of the Fed, thus the reason why the shock has a weak explanatory power.

## 5 Conclusions

The TVP-VAR methodology has been gaining ground over the past years. Whereas the original developers of the method, Cogley and Sargent (2005), and Primiceri (2005), used it to investigate the evolution of the US monetary policy, a few papers have used the method to conduct similar study on fiscal policy. Yet, as Rossi and Zubairy (2011) point out, one needs to consider jointly the monetary and fiscal shocks and condition both policies on each other in order to produce unbiased estimates. In addition, a solid identification scheme of shocks using sign restrictions is necessary if one wishes to separate the effects from a set of shocks. We combine all three methodological advances in our examination of the fiscal-monetary policy interactions in the US since 1980, and analyze mainly three aspects. First, we look at the evolution of the US economic structure and identify possible structural shifts, both in terms of the shock structures and the endogenous responses to those shocks. Second, we investigate the US fiscal-monetary interplays and establish various coor-

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<sup>31</sup>Similar observations are made in Rossi and Zubairy (2011).

<sup>32</sup>The two fiscal shocks together explain between 17 and 30 percent of the interest rate volatility.

dination regimes. Third, we examine the fiscal transmission channel and determine the efficiency of fiscal policy in stabilizing output.

The paper makes four principal contributions. First, we observe significant time variation in the model parameters (and error volatilities) between 1979 and 2012. All our results confirm that there are three regimes in US economy: the Volcker chairmanship (1979-84), the Great Moderation (1985-2007), and the Great Recession (2008-12). Second, impulse responses show that there are significant interactions between monetary and fiscal policies over time. Depending on the shocks and time period considered, we observe significant differences. Third, decomposition of forecast error variance in spending shows that spending itself is largely acyclical, indicating strong inertias and path-dependencies in government spending decisions. In addition, we find that while government revenues largely influence decisions on government spending, government spending does not influence tax decisions. Fourth and final, our analysis of the fiscal transmission channel reveals two things. Tax cuts, because of their crowding-in effects, are more efficient in expanding the economy than government spending rises, since the tax multiplier is higher and more persistent. In light of the current recession, the fiscal authorities should therefore concentrate their efforts on cutting taxes. Coupled with the currently very accommodative monetary policy, it does not only result in a significant short-run expansion of output, but the impact is long-lasting and increasing, since the medium/long-run multiplier has been 1.2 during the Great Recession (2007-12). If authorities manage the expectations of the private agents, the expansionary effects of tax cuts might be even larger, as they were during the Volcker chairmanship when the medium/long-run multiplier was 1.8. Taking into account that the interest rate is at its zero lower bound, the authorities will need to carefully manage the expectations of the private agents and strike a balance between the agents perceiving the tax cuts as temporary (and not to be perceived as if they will remain beyond the period over which monetary policy is constrained by the zero lower bound) and them not expecting a too rapid reversal in the tax cuts (which would counteract the positive effects from the initial tax cuts). The final success of tax cuts will, however, depend on the delicate management of private agent expectations jointly by the two authorities.

Using recently developed (single and multiple) structural break tests such as Andrews (1993), Nyblom (1989), Elliott and Müller (2006), and Bai and Perron (1998), future research should validate the structural shifts identified here and examine whether in 1984-85 the US economy underwent a structural break, and whether the

same re-occurred in 2008. Finally, it would be interesting to extend our framework to counterfactuals, possibly by using a DSGE-model that accommodates for the two policies, and discuss the optimal combination of fiscal-monetary policies in order to achieve certain macroeconomic targets. Fernandez-Villaverde et al (2011) is a first step in this direction.

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## A Appendix: Identification scheme

The following table outlines the sign-restrictions used for identifying the four shocks.

Table A.1: Imposed Signs on the Impulse Responses

	Spending	Net Taxes	Output	Inflation	Interest rate
Spending shock	+		+		
Tax shock		+	-		
Business cycle shock		+	+		
Monetary policy shock			-	-	+

*Notes:* A blank entry indicates no restriction on the specific combination of shock and response.

## B Bayesian Estimation

The appendix goes through our Bayesian estimation strategy in detail; it draws heavily on the expositions in Primiceri (2005) and Canova and Gambetti (2009). As a notational convention, a generic vector or matrix  $x^\tau$  consists of a sequence of observable variables or estimates up to time  $\tau$ , i.e.  $x^\tau = \{x_t\}_{t=1}^\tau$ . We express the realization as  $z_t$  conditional on an information set, say,  $x^\tau$  as  $z_{t|\tau}$  and, likewise, abbreviate the conditional mean and variance of an arbitrary parameter  $\theta$  as  $\theta_{t|\tau}$  and  $V_{t|\tau}^\theta$ . The function  $p(\cdot)$  denotes a generic density and  $\dim(\cdot)$  specifies the dimension of a vector.

### B.1 Priors

An obvious choice to calibrate the priors, and the one pursued here, are simple estimates from time invariant least squares (OLS) on (1) over the entire sample as in Canova and Ciccarelli (2009). The positive side effect from using the entire sample, as opposed to Primiceri’s (2005) training sample prior, is the minimization of the uncertainty involved in calibrating the priors properly. To denote the time invariant estimator we will use “hats”.

We follow Canova and Gambetti (2009) and specify the prior densities  $p(\beta_0)$ ,  $p(\alpha_0)$  and  $p(\log \sigma_0)$  for the initial states of the time varying parameters to be normally distributed, and  $p(Q)$ ,  $p(S_i)$  and  $p(W)$  for the hyperparameters to follow an

inverse Wishart. Specifically,

$$\begin{aligned}
p(\beta_0) &\sim N(\hat{\beta}, 4\text{Var}(\hat{\beta})t), \\
p(\alpha_0) &\sim N(\hat{\alpha}, 4\text{Var}(\hat{\alpha})), \\
p(\log \sigma_0) &\sim N(\log \hat{\sigma}, I_k), \\
p(Q) &\sim IW((0.0003 \cdot (\dim(\hat{\beta}) + 1) \cdot \text{Var}(\hat{\beta}))^{-1}, \dim(\hat{\beta}) + 1), \\
p(S_i) &\sim IW((0.001 \cdot (i + 1) \cdot \hat{S}_i)^{-1}, i + 1), \quad i = 1, \dots, k - 1, \\
p(W) &\sim IW((0.001 \cdot (\dim(\hat{\sigma}) + 1) \cdot I_k)^{-1}, \dim(\hat{\sigma}) + 1).
\end{aligned}$$

The setup of prior densities is more or less standard in the TVP-VAR literature, although slight differences can be found for the specification of  $p(Q)$  with minor effects on the results. Primiceri (2005), in a trivariate TVP-VAR with two lags, uses a factor of 0.0001 and a fixed value of 40 for the degrees of freedom. Because of the hierarchical structure imposed by the laws of motion (11), (12) and (13) the choice of prior densities leads to normal priors for the entire sequence  $\{\beta_t, \alpha_t, \log \sigma_t\}_{t=1}^T$ . For the inverse Wishart distribution to have a proper prior the degrees of freedom must exceed the dimension of the respective hyperparameter at least by one; a choice of "just one" puts then as little weight as possible on the prior.<sup>33</sup> In general, the above specification transforms the information from the time invariant OLS estimates into diffuse and uninformative priors.

## B.2 Gibbs Sampler

The Gibbs sampling algorithm involves three blocks of conditional distributions for all the parameters in the model: the coefficient states  $\beta_t$ , the covariance states  $\alpha_t$ , and the volatility states  $\sigma_t$ . The first two blocks can easily be cast into a linear and Gaussian state space form and therefore the standard algorithm for Gibbs sampling of Carter and Kohn (1994) can be used. Drawing volatility states is a bit more tricky as they have a nonlinear and non-Gaussian state space form. Kim, Shephard, and Chib (1998) provide a linear and approximately Gaussian reformulation of the problem with the advantage of restoring the assumptions needed for the Carter-Kohn algorithm to work. Step 1 below describes the algorithm in detail. For the other steps it suffices to show the setup of the state space.

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<sup>33</sup>As the inverse Wishart distribution is a conjugate prior for the covariance matrix of the corresponding time varying parameters  $\beta_t, \alpha_t$  and  $\log \sigma_t$  the scale factor has to be a multiple of the time invariant variance matrices used to calibrate the prior for the initial states.

*Step 1: Coefficient states and algorithm in detail.* — Equations (10) and (12), rewritten here for convenience,

$$y_t = X_t' \beta_t + u_t \quad \text{and} \quad \beta_t = \beta_{t-1} + \nu_t, \quad (\text{B.1})$$

constitute a state space model in which both  $u_t$  and  $\nu_t$  are normally distributed with a zero mean and variances  $\Omega_t$  and  $Q$ . Further, the block diagonal structure of (14) assumes that  $u_t$  and  $\nu_t$  are mutually uncorrelated. Now, conditional on the data,  $\alpha^T$ ,  $\sigma^T$ ,  $s^T$  and  $V$  the variance  $\Omega_t$  in the observation equation is known from (7) and we can therefore generate the whole sequence  $\beta^T$  as in Lemma 2.1 of Carter and Kohn (1994):

$$p(\beta^T | y^T, \alpha^T, \sigma^T, s^T, V) = p(\beta_T | y^T, \alpha^T, \sigma^T, s^T, V) \prod_{t=1}^{T-1} p(\beta_t | \beta_{t+1}, y^t, \alpha^t, \sigma^t, s^t, V).$$

The function of  $s^T$  will become clear momentarily in Step 3. Then, to get  $\beta^T$  from  $p(\beta^T | y^T, \dots)$  we, first, generate  $\beta_T$  from  $p(\beta_T | y^T, \dots) = N(\beta_{T|T}, V_{T|T}^\beta)$  and, second, for  $t = T - 1, \dots, 1$  we draw  $\beta_t$  from  $p(\beta_t | \beta_{t+1}, y^t, \dots) = N(\beta_{t|t+1}, V_{t|t+1}^\beta)$ . Starting from  $\beta_{0|0} = \hat{\beta}$  and  $V_{0|0}^\beta = \text{Var}(\hat{\beta})$  the Kalman filter recursion over  $t = 1, \dots, T$ , i.e.

$$\begin{aligned} \beta_{t|t-1} &= \beta_{t-1|t-1}, \\ V_{t|t-1}^\beta &= V_{t-1|t-1}^\beta + Q, \\ \beta_{t|t} &= \beta_{t|t-1} + V_{t|t-1}^\beta X_t \left( X_t' V_{t|t-1}^\beta X_t + \Omega_t \right)^{-1} (y_t - X_t' \beta_{t|t-1}) \quad \text{and} \\ V_{t|t}^\beta &= V_{t|t-1}^\beta - V_{t|t-1}^\beta X_t \left( X_t' V_{t|t-1}^\beta X_t + \Omega_t \right)^{-1} X_t' \beta_{t|t-1}, \end{aligned}$$

leads to a draw of  $\beta_T$  from the normal distribution using the elements  $\beta_{T|T}$  and  $V_{T|T}^\beta$  from the last recursion. We now plug the results of the filter and the draw of  $\beta_T$  into a reversed version of the Kalman filter to derive  $\beta_{T-1|T}$   $V_{T-1|T}^\beta$ . This backward updating delivers a draw for  $\beta_{T-1}$  and so forth until we arrive at  $\beta_1$ . Specially, the backward updating steps for  $t = T - 1, T - 2, \dots, 1$  are

$$\begin{aligned} \beta_{t|t+1} &= \beta_{t|t} + V_{t|t}^\beta \left( V_{t|t}^\beta + Q \right)^{-1} (\beta_{t+1} - \beta_{t|t}) \quad \text{and} \\ V_{t|t+1}^\beta &= V_{t|t}^\beta - V_{t|t}^\beta \left( V_{t|t}^\beta + Q \right)^{-1} V_{t|t}^\beta. \end{aligned}$$

For more details on Gibbs sampling for state space models and the Kalman filter

see Carter and Kohn (1994) and Anderson and Moore (1979).

Then, given  $\beta^T$ , we can observe the innovation  $\nu_t$  in (12) and draw the hyperparameter  $Q$  from the inverse Wishart distribution with scale parameters  $(0.0003 \cdot (\dim(\hat{\beta}) + 1) \cdot \text{Var}(\hat{\beta}) + \sum_{t=1}^T \Delta\beta_t \Delta\beta_t')^{-1}$  and degrees of freedom  $\dim(\hat{\beta}) + 1 + T$ .

*Step 2: Covariance states.* — While the state equation for  $\alpha_t$  is readily available from (11), the derivation of the observation equation requires some work. Omitting the orthonormal rotation matrix  $G_t$  which is not part of the estimation stage, let us write (10) as

$$A_t u_t = \Sigma_t \varepsilon_t \quad \text{with } u_t = (y_t - X_t' \beta_t). \quad (\text{B.2})$$

Conditional on  $\beta^T$  we can observe the reduced-form residuals  $u_t$  and given the triangular form of the  $\alpha_t$ 's we can rewrite (B.2) as

$$u_t = Z_t \alpha_t + \Sigma_t \varepsilon_t, \quad (\text{B.3})$$

with

$$Z_t = \begin{bmatrix} 0 & 0 & 0 & 0 \\ [-u_{i,t}] & 0 & 0 & 0 \\ 0 & [-u_{x,t}, -u_{g,t}] & 0 & 0 \\ 0 & 0 & [-u_{x,t}, -u_{g,t}, -u_{t,t}] & 0 \\ 0 & 0 & 0 & [-u_{x,t}, \dots, -u_{\pi,t}] \end{bmatrix}.$$

It becomes now obvious why assuming  $S$  to be block diagonal in (14) reduces the complexity of the Bayesian estimation. Under the block diagonality we can splice up the state space model in separate equations. Splicing up the model in this manner restores the exogeneity requirement of the Kalman filter and we can apply the algorithm of Carter and Kohn (1994), as laid out in Step 1, equation by equation. To formalize these separate equations let  $[ij] = i, \dots, j$  and  $[rs] = r, \dots, s$  denote two indices running from  $i$  to  $j$  and  $r$  to  $s$ . Now write (B.3) as

$$u_{[ij],t} = \mu_{[ij],t} + Z_{[ij],t} \alpha_{[rs],t} + \Sigma_{[ij],t} \varepsilon_{[ij],t} \quad (\text{B.4})$$

in which the indices in brackets,  $i = 2, j = 2, \dots, 4, r = 1, 2, 4$  and  $s = r + j - 2$ , select the required subvectors and matrices for the  $k - 1 = 4$  equations.

*Step 3: Volatility states*  $p(\sigma^T | y^T, \beta^T, \alpha^T, s^T, V)$ . — Drawing  $\sigma^T$  relies on the algorithm of Kim, Shephard, and Chib (1998), a procedure to transform an otherwise

nonlinear and non-Gaussian state space model into a linear and approximately normal one. The standard algorithm of Carter and Kohn (1994), as laid out in Step1, is therefore again available. The observation equation can be written as

$$A_t(y_t - X_t'\beta_t) = e_t \quad \text{with } e_t = \Sigma_t \varepsilon_t. \quad (\text{B.5})$$

Given  $y^T$ , and  $\beta^T$  and  $\alpha^T$  from the two previous Gibbs sampling block  $e_t$  is observable. Since we have defined the law of motion (13) for the diagonal entries of  $\Sigma_t$  as a geometric random walk, we can convert (B.5) into the appropriate form by squaring and taking the logarithm. We then obtain the “linearized” state space model

$$e_t^* = 2 \log \sigma_t + \xi_t \quad \text{and} \quad \log \sigma_t = \log \sigma_{t-1} + \eta_t, \quad (\text{B.6})$$

in which  $e_{i,t}^* = \log(e_{i,t}^2 + 0.001)$  and  $\xi_{i,t} = \log(\varepsilon_{i,t}^2)$  for  $i = (g, t, x, \pi, i)$ ; the offset constant 0.001 deals with very small values of  $e_{i,t}^2$  as in Kim, Shephard and Chib (1998); and the innovation  $\xi_t$  follows a  $\log \chi^2(1)$  distribution. While this conversion restores the linearity assumption the distributional form of  $\xi_t$  still precludes direct and simple inference. Kim, Shephard and Chib (1998) show how to accurately approximate the  $\log \chi^2(1)$  distribution through a matched mixture of seven Normal distributions,

$$f(\xi_{i,t}) \approx \sum_{j=1}^7 p_j N(\xi_{i,t} | m_j - 1.2704, v_j^2), \quad i = (g, t, x, \pi, i), \quad (\text{B.7})$$

in which  $N(\xi_{i,t} | m_j - 1.2704, v_j^2)$  denotes the density function of a normal distribution with mean  $m_j - 1.2704$  and variance  $v_j^2$ . Values for  $p_j$ ,  $m_j$  and  $v_j^2$  are reproduced in Table B.1. Conditional on  $s^T$  we can draw a value for  $\xi_{i,t} | s_{i,t} = j \sim N(m_j - 1.2704, v_j^2)$  and proceed as in Step 1 to draw  $\log \sigma_{i,t}$  for all  $i$  and  $t$ . Given these draws of  $\xi_{i,t}$  we independently sample the indicator matrix  $s_{i,t}$  selecting the mixture  $j = 1, \dots, 7$  from the discrete density  $\Pr(s_{i,t} = j | e_t^*, \log \sigma_{i,t})$ , a density which is proportionally determined from the normal density  $N(e_t^* | 2 \log \sigma_{i,t} + m_j - 1.2704, v_j^2)$ .

### B.3 Convergence Diagnostics of the Markov Chain

From theoretical work such as Gelfand and Smith 1990 we know that the Gibbs sampler converges to the “true” joint posterior distribution as the number of iterations go to infinity. Whether this property holds in the underlying problem with a

Table B.1: Selection of the Mixing Distribution to be  $\log \chi^2(1)$ .

$j$	$p_j$	$m_j$	$v_j^2$	$j$	$p_j$	$m_j$	$v_j^2$
1	0.00730	-10.12999	5.79596	5	0.34001	0.61942	0.64009
2	0.10556	-3.97281	2.61369	6	0.24566	1.79518	0.34023
3	0.00002	-8.56685	5.17950	7	0.25750	-1.08819	1.26261
4	0.04395	2.77786	0.16735				

Notes: Replication of Table 4 in Kim, Shephard, and Chib (1998).

finite number is an important question which we address here.

We implement three MCMC convergence diagnostics for the 20,000 saved draws of each parameter and hyperparameter: the sample autocorrelation; the measure of Geweke (1992); and the diagnostic of Raftery and Lewis (1992). Table B.2 reports the results of the diagnostic checks. Because of the sheer amount of parameters the table shows summary statistics, grouped into hyperparameters  $V$ , coefficients  $\beta^T$ , covariances  $\alpha^T$  and volatilities  $\sigma^T$ . Moreover, each summary statistic reports two values based on the first and last 1,500 draws from the 20,000 saved iterations. This testing strategy adds another layer to the formal MCMC diagnostics: if the Markov chain is in an equilibrium state the medians and percentiles of the two splits should be of roughly equal size.

The 20-th order sample autocorrelations summarized in Panel A of Table B.2 show a relatively low degree of autocorrelation. Only a few hyperparameters  $V$  exhibit statistics higher than 0.2. The draws are therefore almost independent, an indication for the efficiency of the Gibbs sampler and for accurate posterior estimates. Related to that is the inefficiency factor, as measured by the inverse of the relative numerical efficiency statistic of Geweke (1992) with a 4 percent tapered window for the estimation of the spectral density at frequency zero. If the draws come from an independent and identically distributed (iid) sample, drawn directly from the posterior distribution, the inefficiency factor has a value of one. For instance, in Panel B of Table B.2 the median value of 15.81 for the first 1,500 draws of the hyperparameters  $V$  indicates that one would need about 16 times as many draws to achieve the same numerical efficiency as the iid benchmark. Since only values above 20 are considered to be critical and 24.81 is the largest 95-th percentile here the efficiency diagnostic can be regarded as satisfactory. Finally, Raftery and Lewis (1992) provide a measure of the number of draws actually required to achieve a cer-

Table B.2: Convergence Diagnostics of the Markov Chain

	First block of 1,500 draws			Last block of 1,500 draws		
	Median	5-th	95-th	Median	5-th	95-th
<i>A. 20-th Order Sample Autocorrelations</i>						
V	0.19	0.04	0.36	0.19	0.02	0.39
$\beta^T$	0.06	0.00	0.15	0.07	-0.00	0.15
$\alpha^T$	0.02	-0.03	0.12	0.03	-0.00	0.09
$\sigma^T$	0.01	-0.04	0.08	0.01	-0.04	0.08
<i>B. Inefficiency Factor</i>						
V	15.81	9.08	23.47	16.02	8.88	24.81
$\beta^T$	5.45	2.75	9.79	5.46	2.89	10.59
$\alpha^T$	3.53	0.87	8.00	4.30	0.69	6.85
$\sigma^T$	3.08	1.96	6.38	3.19	1.84	6.26

*Notes:* Summary of the distributions of the 20-th order sample autocorrelations and the inefficiency factors (the inverse of Geweke’s (1992) measure of relative numerical efficiency with a 4 percent tapering of the spectral window at frequency zero). “10-th” and “90-th” denote the 5-th and 95-th percentiles. Statistics bases on the first and last 1,500 draws of the 20,000 saved draws. We run 50,000 burn-in draws and set the thinning factor equal to three.

tain accuracy. I specify the parameters for the diagnostic as in Primiceri (2005): a “quantile” of 0.025, a desired “accuracy” of 0.025, and the “probability” of attaining the accuracy equals 95 percent. The maximum number over the whole parameter space for the Raftery and Lewis (1992) diagnostic is 3,082 and thus well below the 20,000 draws used in the analysis. All three diagnostics and the comparison of the sample splits seem satisfactory.



Table 1: Forecast Error Variance Decompositions: Sign Restrictions

Variables	Horizon	Identified Shocks			
		Spending	Tax	Bus. Cycle	Monetary
<i>A. Volcker Chairmanship (1979-1984)</i>					
Spending	1	55.8	17.7	0.7	16.2
	4	52.9	17.2	0.8	15.2
	8	50.2	16.9	0.9	14.4
	20	43.5	17.9	1.3	13.3
Net Taxes	1	6.3	58.3	1.5	20.6
	4	5.7	24.9	3.9	16.9
	8	11.4	22.1	3.2	17.6
	20	17.9	21.7	2.2	16.7
Output	1	30.3	36.8	11.7	1.5
	4	28.5	38.1	12.4	1.5
	8	29.8	42.2	10.3	1.5
	20	33.2	47.1	7.0	1.3
Inflation	1	17.2	19.0	22.2	10.1
	4	18.8	17.9	22.2	10.9
	8	18.3	17.5	22.3	10.9
	20	18.8	17.4	22.4	10.9
Interest Rate	1	12.2	11.8	28.0	10.6
	4	12.2	10.5	32.3	6.7
	8	14.9	12.5	29.2	7.8
	20	17.9	13.5	26.2	8.5
<i>B. Great Moderation (1985-2006)</i>					
Spending	1	51.4	17.9	0.6	21.4
	4	48.0	17.6	0.7	19.0
	8	44.9	17.1	0.8	17.2
	20	37.3	17.0	1.3	14.7
Net Taxes	1	6.4	57.6	1.3	23.3
	4	4.9	18.5	4.0	11.9
	8	8.7	16.4	3.7	12.1
	20	16.6	17.1	2.3	14.2
Output	1	29.4	34.3	12.8	0.6
	4	27.6	36.2	13.1	0.6
	8	28.4	38.8	11.9	0.7
	20	33.1	43.5	8.2	1.0

*(continued on next page)*

Table 1 (*sign restrictions continued*)

Variables	Horizon	Identified Shocks			
		Spending	Tax	Bus. Cycle	Monetary
Inflation	1	13.5	15.5	23.4	6.1
	4	17.0	14.0	23.1	9.5
	8	16.8	14.0	23.3	9.7
	20	17.0	13.9	23.7	9.8
Interest Rate	1	8.4	8.6	29.8	7.3
	4	9.1	7.9	33.0	4.3
	8	10.8	10.1	31.4	5.3
	20	14.7	11.4	27.9	7.2
<i>C. Great Recession (2007-2012)</i>					
Spending	1	43.7	25.6	0.6	21.8
	4	39.7	26.4	0.7	18.7
	8	36.7	26.3	0.9	17.2
	20	29.9	25.9	1.4	15.1
Net Taxes	1	4.6	57.5	0.8	26.1
	4	3.1	15.4	2.9	12.6
	8	5.2	14.6	2.8	13.1
	20	10.1	16.8	1.9	15.7
Output	1	24.4	38.2	13.5	0.9
	4	23.0	42.3	12.6	0.8
	8	24.0	45.4	11.2	0.9
	20	28.5	49.9	7.8	1.3
Inflation	1	14.7	15.7	23.4	8.8
	4	17.7	13.3	23.0	12.3
	8	17.3	13.1	23.4	12.0
	20	17.1	13.0	24.0	11.8
Interest Rate	1	8.5	8.7	29.5	6.5
	4	11.5	10.0	29.6	5.8
	8	12.7	12.1	28.3	7.5
	20	14.8	12.7	26.4	9.1

*Notes:* Posterior means of the percent of forecast error variance attributed to our four shocks.

Table 2: Forecast Error Variance Decompositions: Recursive Identification

Variables	Horizon	Identified Shocks			
		Spending	Tax	Bus.Cycle	Monetary
<i>A. Volcker Chairmanship (1979-1984)</i>					
Spending	1	55.8	17.7	0.7	16.2
	4	52.9	17.2	0.8	15.2
	8	50.2	16.9	0.9	14.4
	20	43.5	17.9	1.3	13.3
Net Taxes	1	6.3	58.3	1.5	20.6
	4	5.7	24.9	3.9	16.9
	8	11.4	22.1	3.2	17.6
	20	17.9	21.7	2.2	16.7
Output	1	30.3	36.8	11.7	1.5
	4	28.5	38.1	12.4	1.5
	8	29.8	42.2	10.3	1.5
	20	33.2	47.1	7.0	1.3
Inflation	1	17.2	19.0	22.2	10.1
	4	18.8	17.9	22.2	10.9
	8	18.3	17.5	22.3	10.9
	20	18.8	17.4	22.4	10.9
Interest Rate	1	12.2	11.8	28.0	10.6
	4	12.2	10.5	32.3	6.7
	8	14.9	12.5	29.2	7.8
	20	17.9	13.5	26.2	8.5
<i>B. Great Moderation (1985-2006)</i>					
Spending	1	51.4	17.9	0.6	21.4
	4	48.0	17.6	0.7	19.0
	8	44.9	17.1	0.8	17.2
	20	37.3	17.0	1.3	14.7
Net Taxes	1	6.4	57.6	1.3	23.3
	4	4.9	18.5	4.0	11.9
	8	8.7	16.4	3.7	12.1
	20	16.6	17.1	2.3	14.2
Output	1	29.4	34.3	12.8	0.6
	4	27.6	36.2	13.1	0.6
	8	28.4	38.8	11.9	0.7
	20	33.1	43.5	8.2	1.0

*(continued on next page)*

Table 2 (*recursive identification continued*)

Variables	Horizon	Identified Shocks			
		Spending	Tax	Bus. Cycle	Monetary
Inflation	1	13.5	15.5	23.4	6.1
	4	17.0	14.0	23.1	9.5
	8	16.8	14.0	23.3	9.7
	20	17.0	13.9	23.7	9.8
Interest Rate	1	8.4	8.6	29.8	7.3
	4	9.1	7.9	33.0	4.3
	8	10.8	10.1	31.4	5.3
	20	14.7	11.4	27.9	7.2
<i>C. Great Recession (2007-2012)</i>					
Spending	1	43.7	25.6	0.6	21.8
	4	39.7	26.4	0.7	18.7
	8	36.7	26.3	0.9	17.2
	20	29.9	25.9	1.4	15.1
Net Taxes	1	4.6	57.5	0.8	26.1
	4	3.1	15.4	2.9	12.6
	8	5.2	14.6	2.8	13.1
	20	10.1	16.8	1.9	15.7
Output	1	24.4	38.2	13.5	0.9
	4	23.0	42.3	12.6	0.8
	8	24.0	45.4	11.2	0.9
	20	28.5	49.9	7.8	1.3
Inflation	1	14.7	15.7	23.4	8.8
	4	17.7	13.3	23.0	12.3
	8	17.3	13.1	23.4	12.0
	20	17.1	13.0	24.0	11.8
Interest Rate	1	8.5	8.7	29.5	6.5
	4	11.5	10.0	29.6	5.8
	8	12.7	12.1	28.3	7.5
	20	14.8	12.7	26.4	9.1

*Notes:* Posterior means of the percent of forecast error variance attributed to our four shocks.

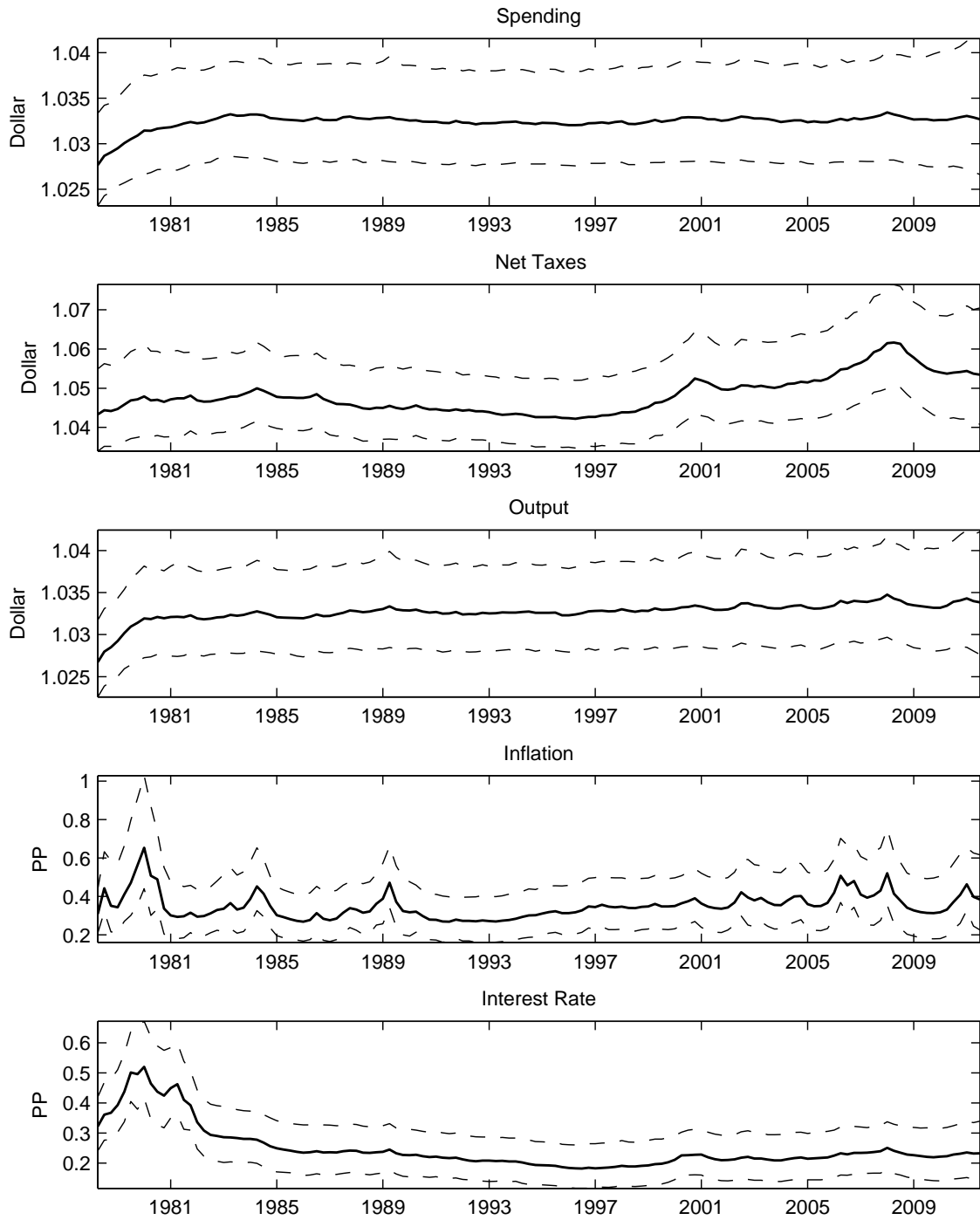


Figure 1: Standard Deviation of Residuals

*Notes:* Posterior median, 16-th and 84-th percentiles of the standard deviation of the TVP-VAR residuals in the spending, tax, output, inflation and interest rate equations. Units on the *y*-axis denote 10,000 real per capita dollars and percentage points (PP).

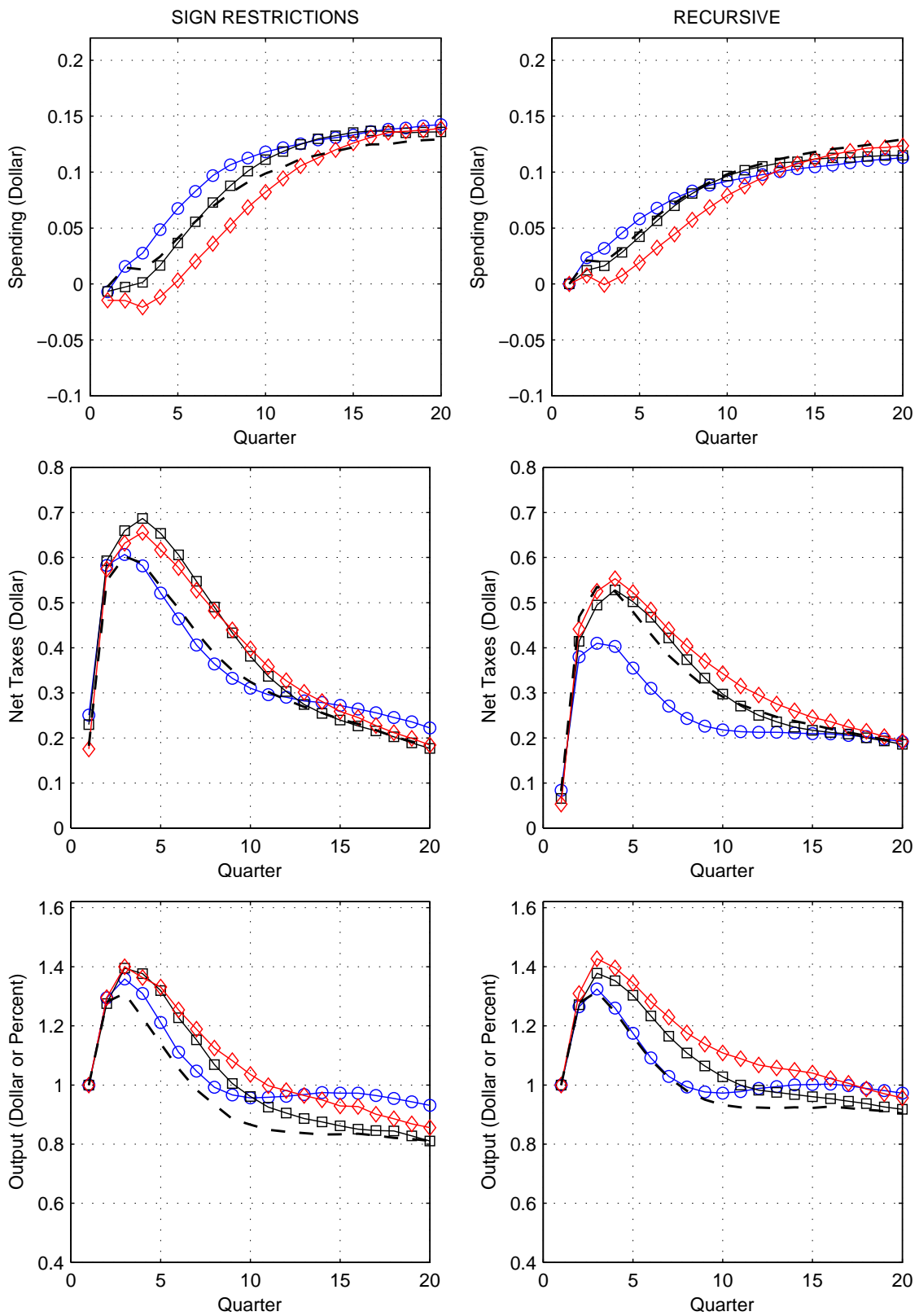
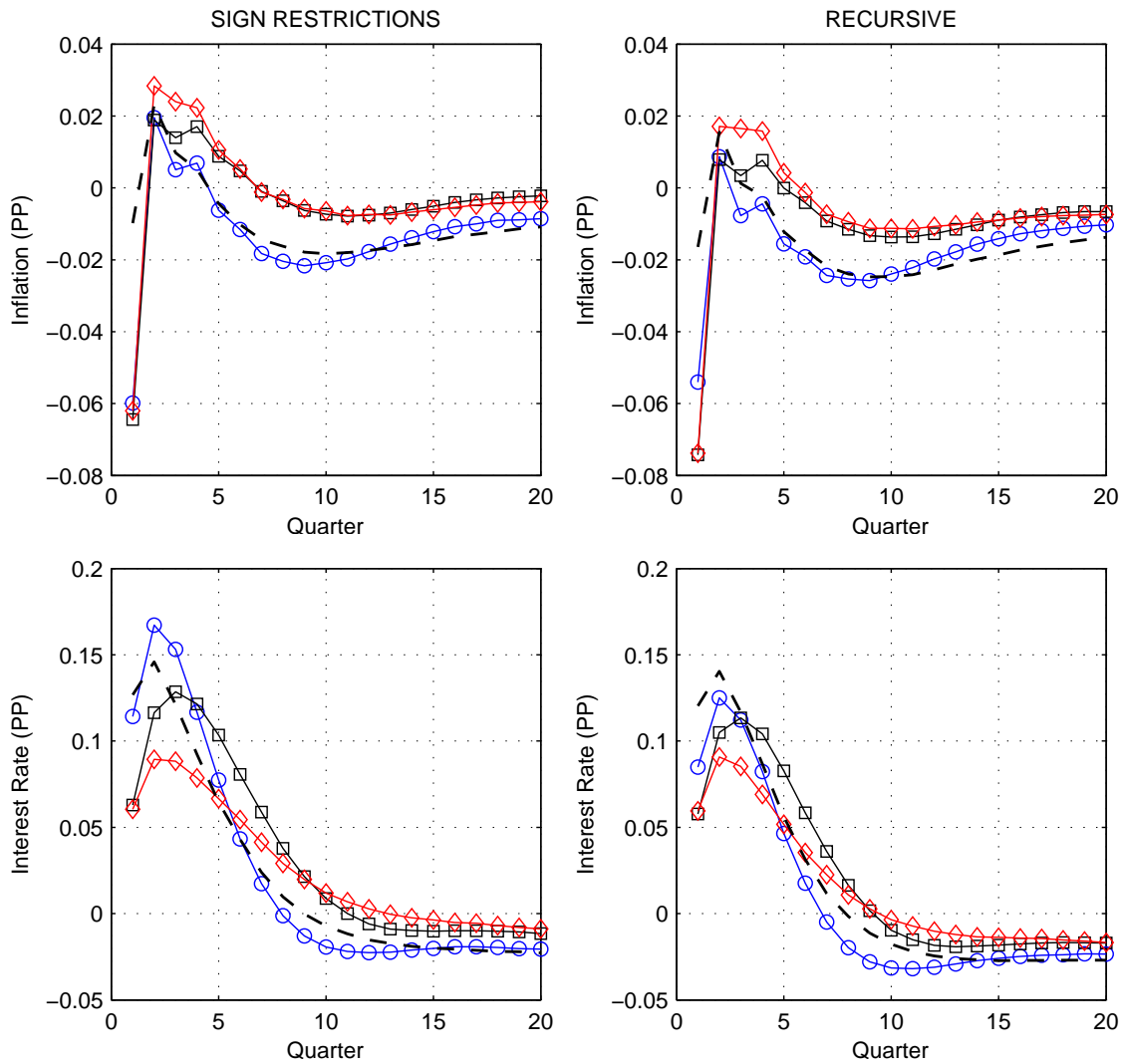


Figure 2: Response to a Business Cycle Shock

*(continued on next page)*

Figure 2 (*business cycle shock continued*)



*Notes:* Median impulse responses of the three episodes, Volcker chairmanship (blue lines with circles), Great Moderation (black lines with squares) and the Great Recession (red lines with diamonds), and comparison of identification methods; results from constant VAR superimposed (black dashed lines). Units are in brackets. The normalized output response represents a one dollar shock to spending and taxes, and a one percent shock to inflation and the short-term interest rate; deviations of the nominal variables from trend are expressed in quarterly percentage points (PP).

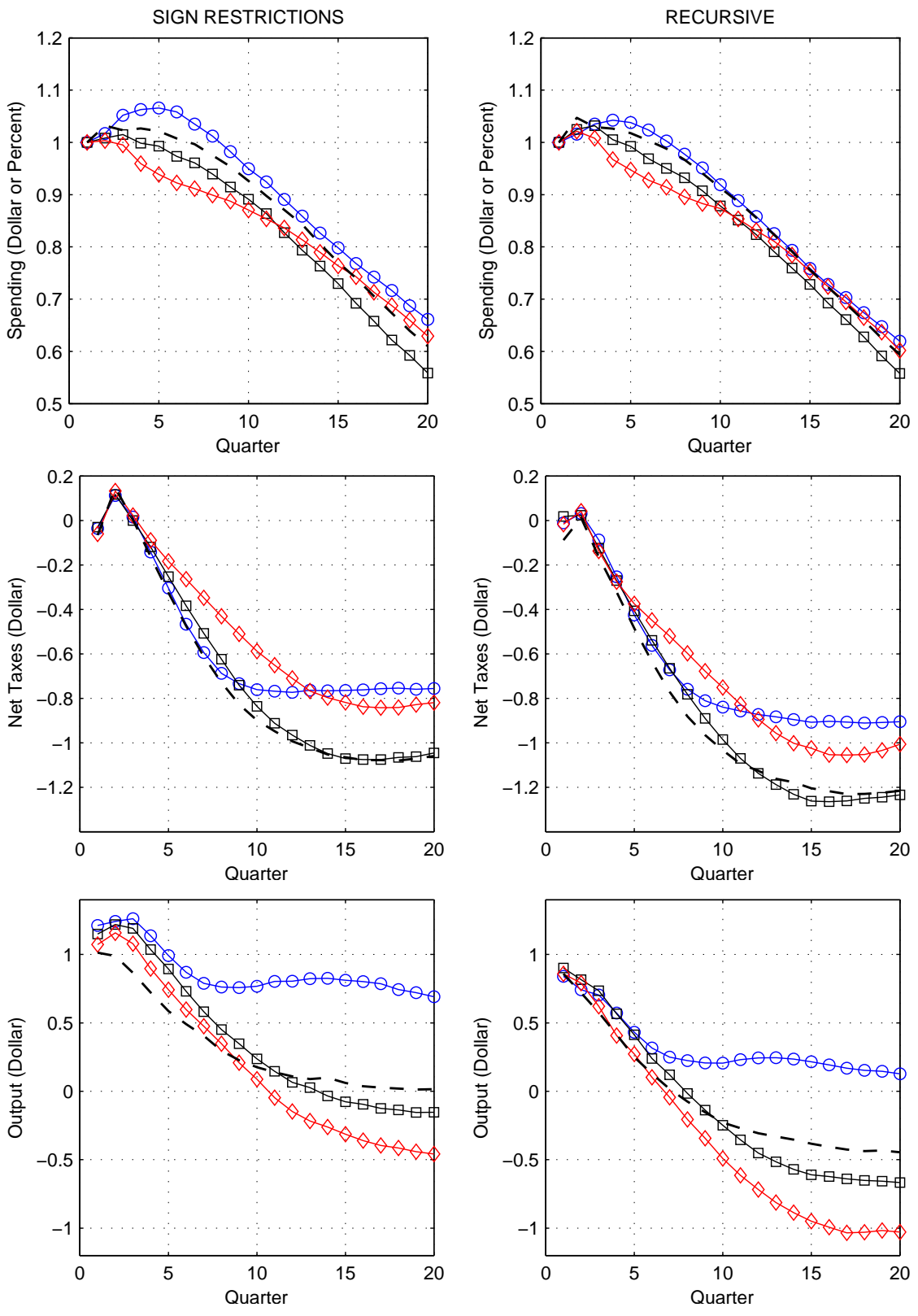
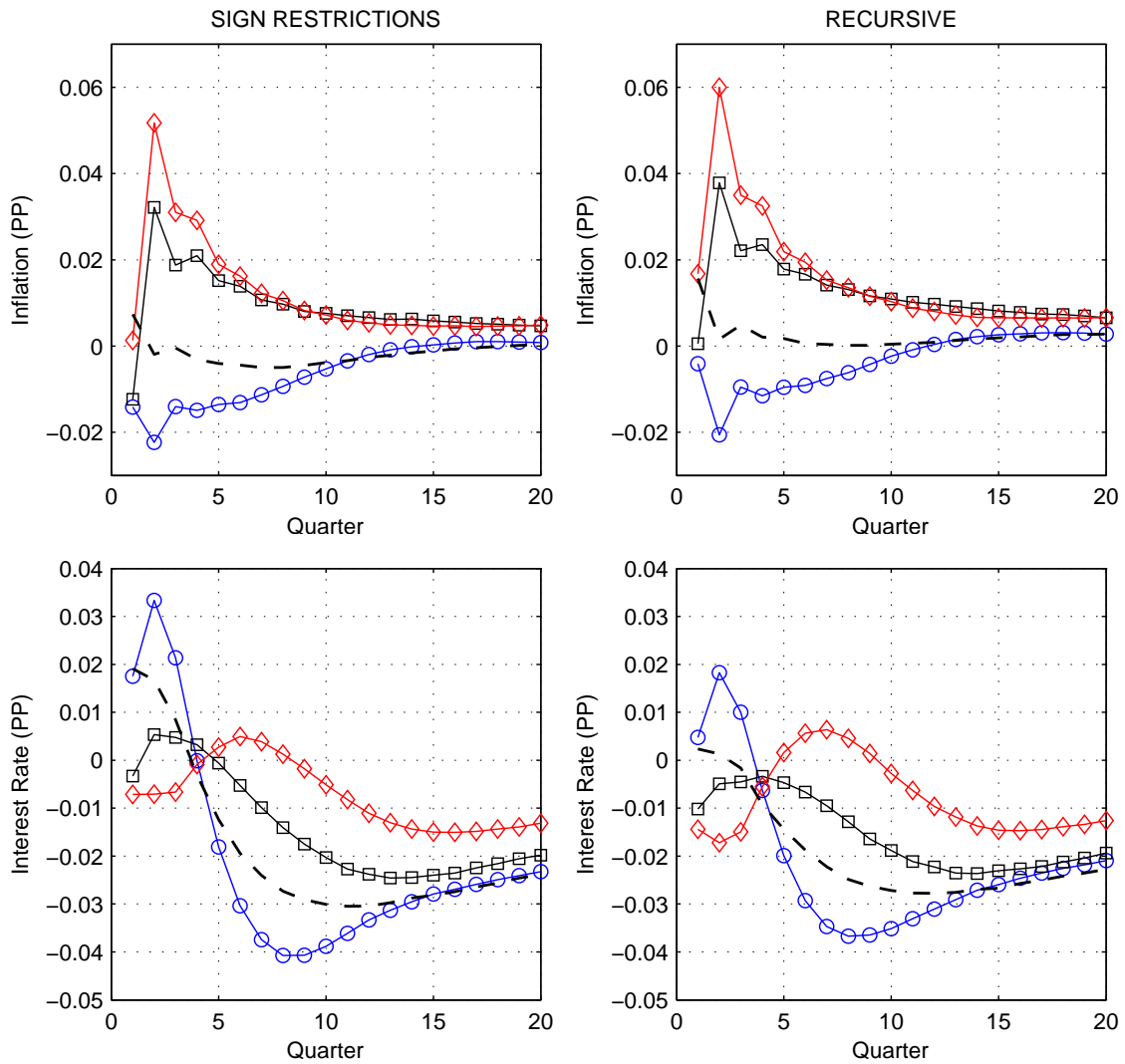


Figure 3: Response to a Spending Shock

(continued on next page)



Figure 3 (*spending shock continued*)



*Notes:* Median impulse responses of the three episodes, Volcker chairmanship (blue lines with circles), Great Moderation (black lines with squares) and the Great Recession (red lines with diamonds), and comparison of identification methods; results from constant VAR superimposed (black dashed lines). Units are in brackets. The normalized spending response represents a one dollar shock to output and taxes, and a one percent shock to inflation and the short-term interest rate; deviations of the nominal variables from trend are expressed in quarterly percentage points (PP).

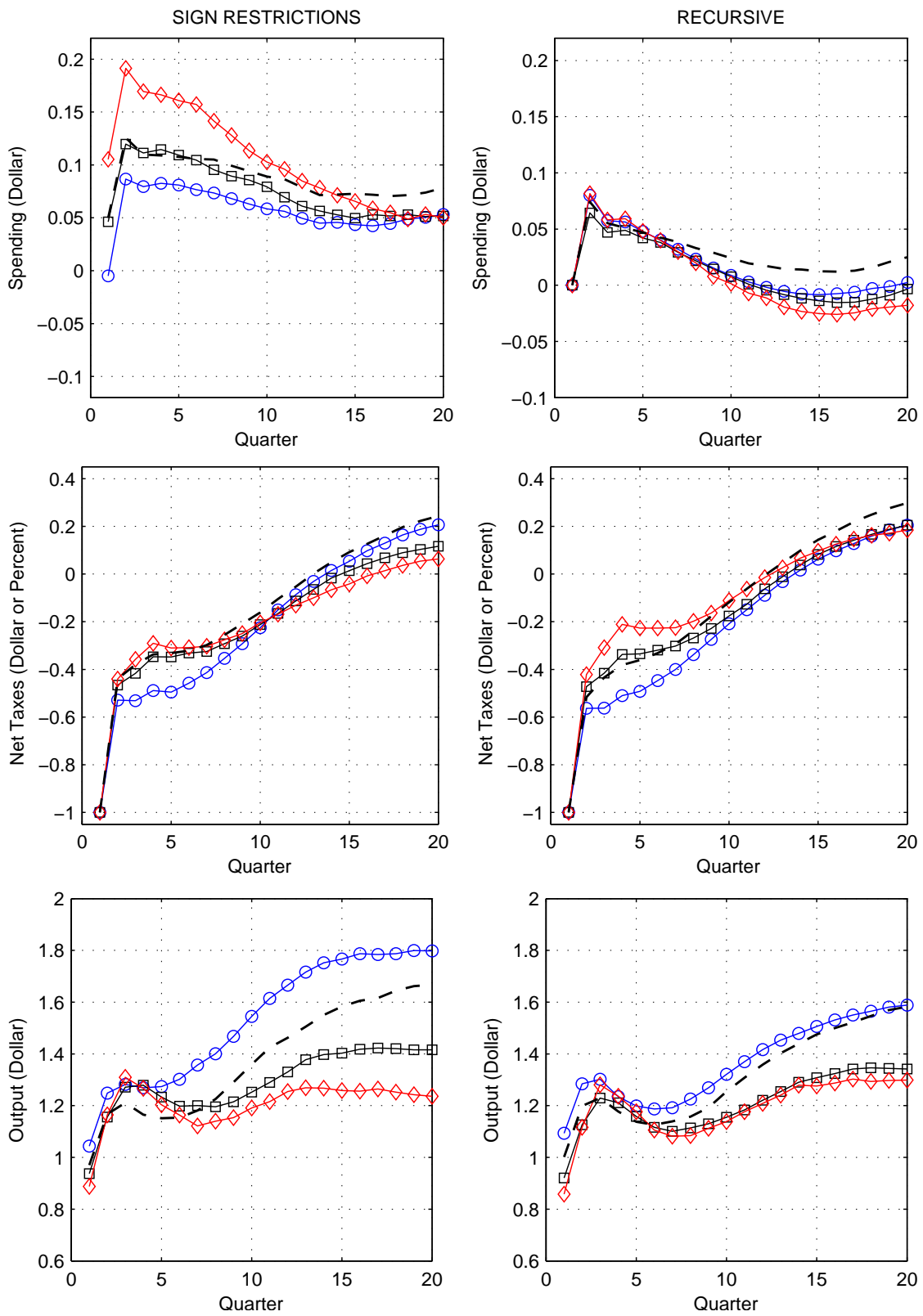
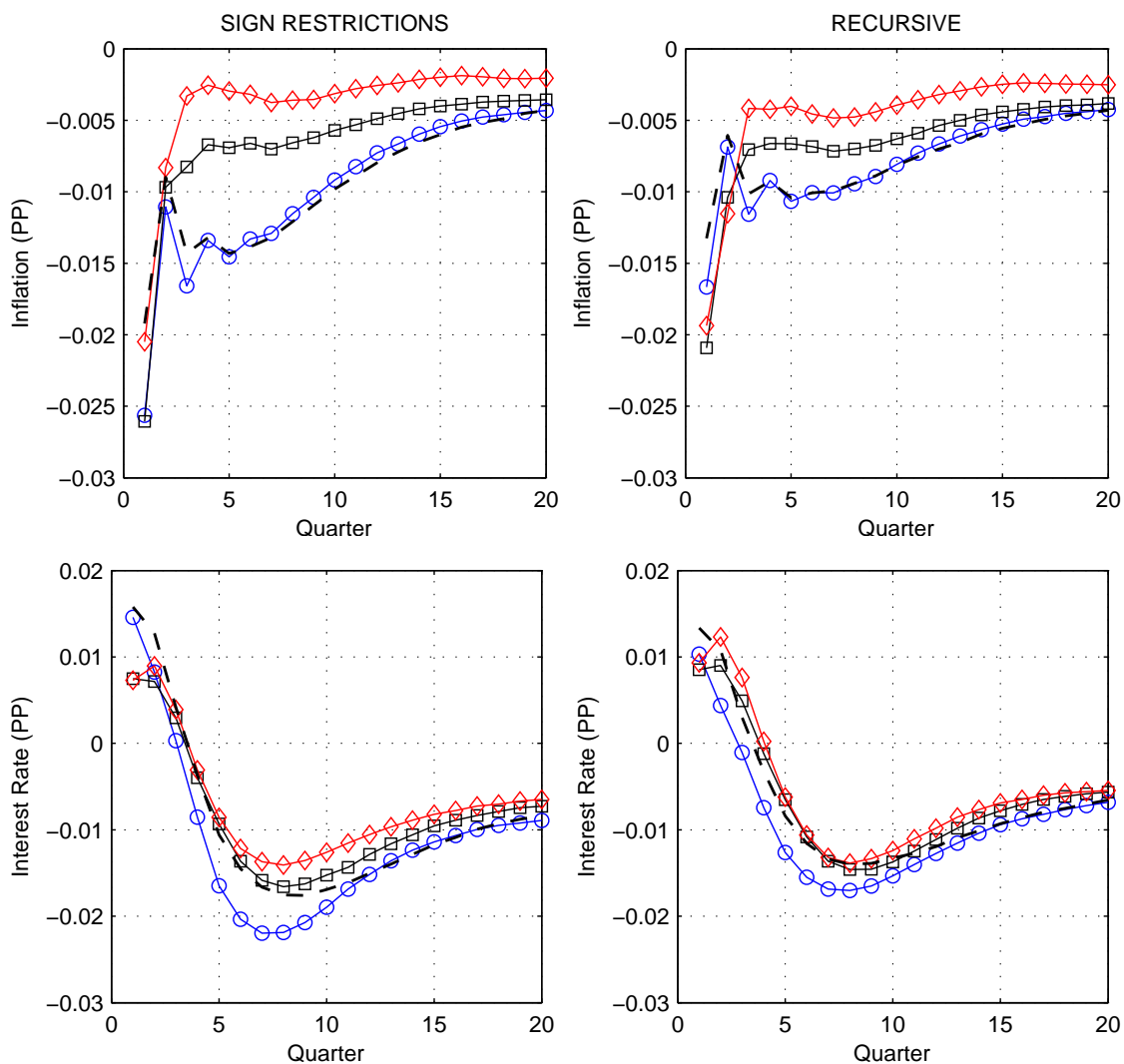


Figure 4: Response to a Tax Shock

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Figure 4 (*tax shock continued*)



*Notes:* Median impulse responses of the three episodes, Volcker chairmanship (blue lines with circles), Great Moderation (black lines with squares) and the Great Recession (red lines with diamonds), and comparison of identification methods; results from constant VAR superimposed (black dashed lines). Units are in brackets. The normalized tax response represents a negative one dollar shock to spending and output, and a negative one percent shock to inflation and the short-term interest rate; deviations of the nominal variables from trend are expressed in quarterly percentage points (PP).

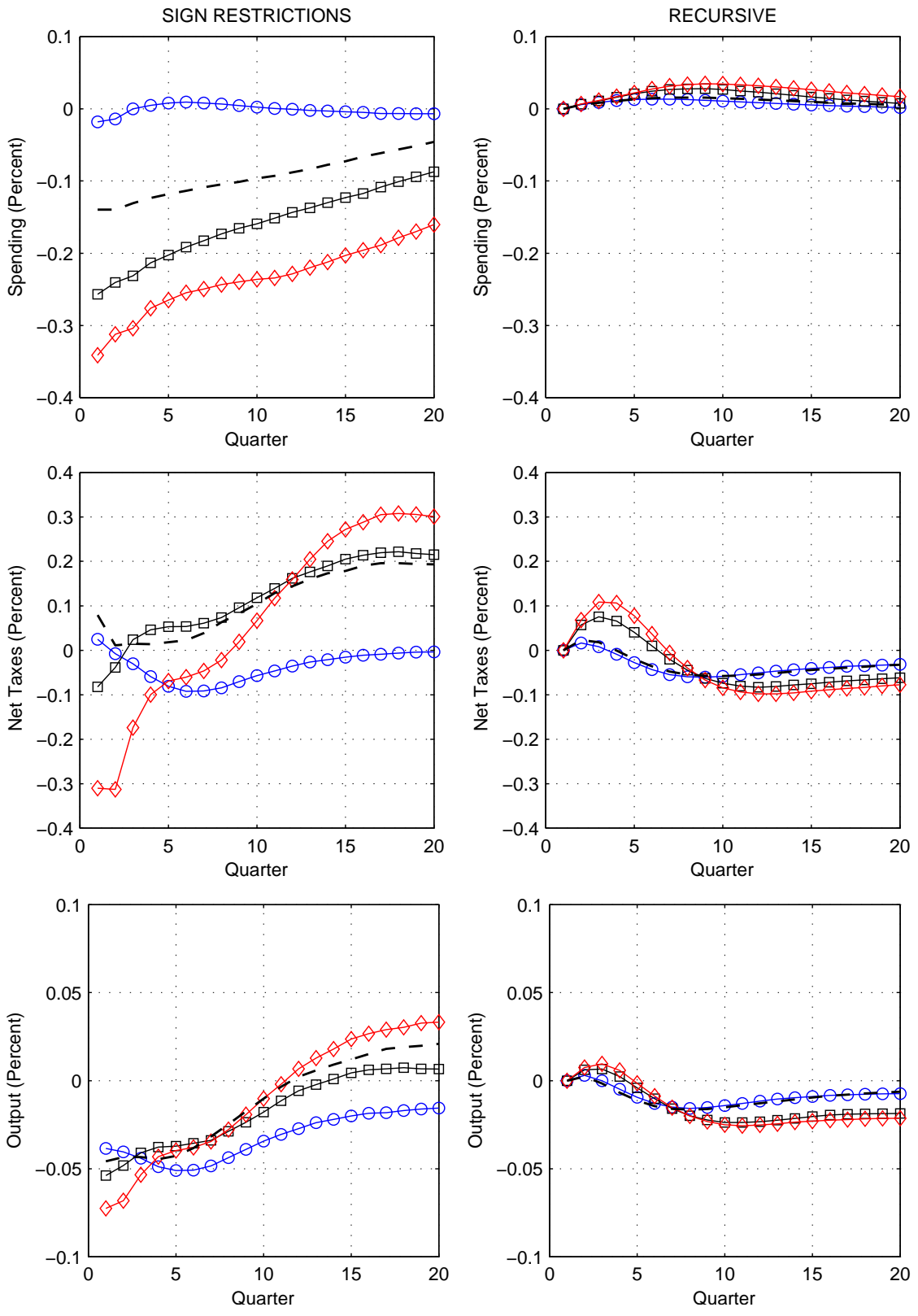
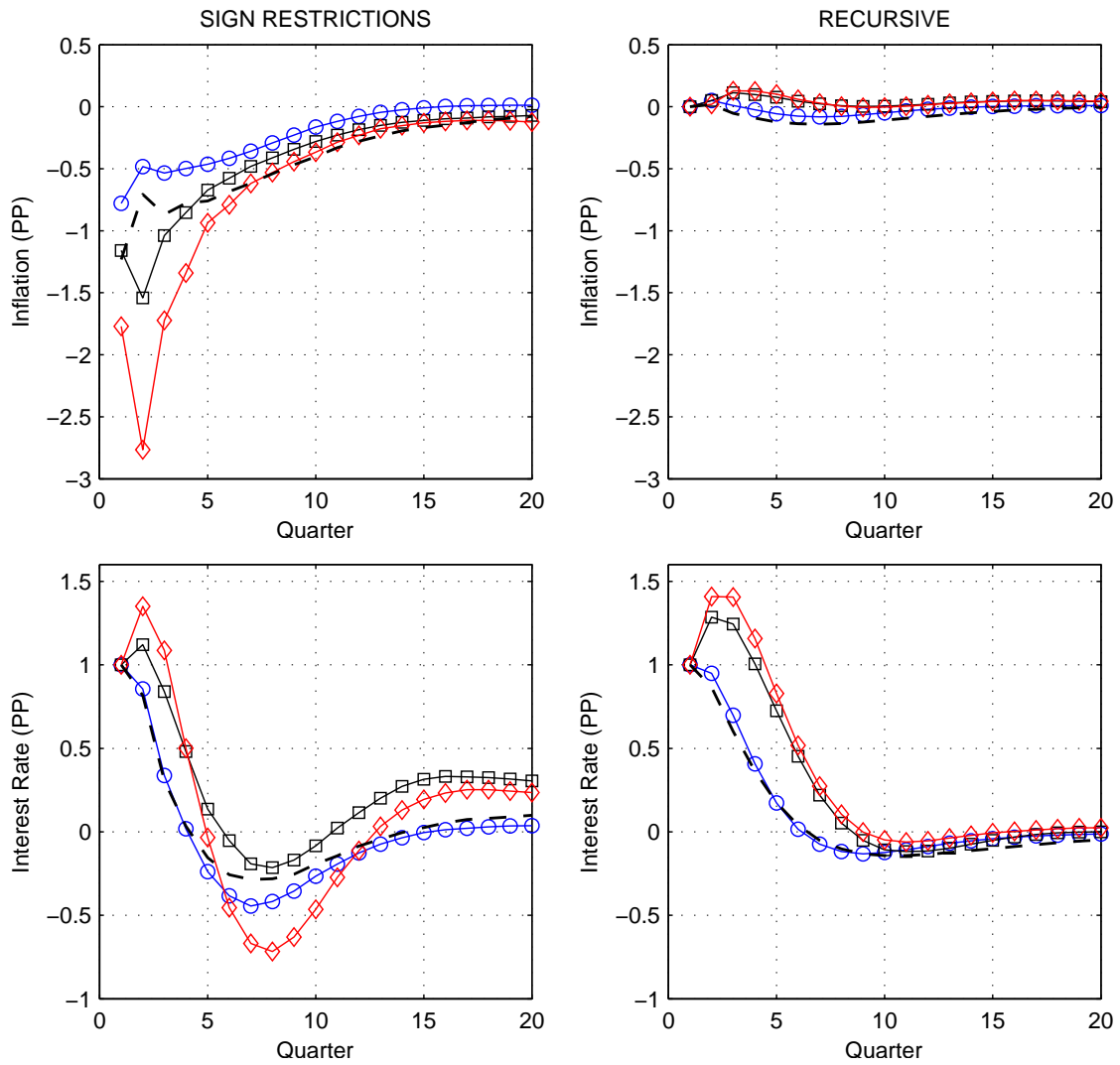


Figure 5: Response to a Monetary Policy Shock

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Figure 5 (*monetary policy shock continued*)



*Notes:* Median impulse responses of the three episodes, Volcker chairmanship (blue line with circles), Great Moderation (black line with squares) and the Great Recession (red line with diamonds), and comparison of identification methods; results from constant VAR superimposed (black dashed lines). Units are in brackets. The normalized response of the short-term interest rate represents a one percentage point (PP) shock.