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ABSTRACT

Technology-Hours Redux: Tax Changes and the Measurement of Technology Shocks*

A number of empirical studies find that permanent technological improvements give rise to a temporary drop in hours worked. This finding seriously questions the technology-driven business cycle hypothesis. In this paper we argue that it is important to control for permanent changes in taxes, which invalidate the standard long run identifying assumptions for technology shocks and induce low frequency fluctuations in hours worked. Using the narrative data of Romer and Romer (2010), we find that tax shocks have significant long run effects on aggregate hours, output and labor productivity. We also find that, after controlling for tax shocks, permanent shocks to labor productivity generate short run increases in hours worked and are an important source of fluctuations in US output.

JEL Classification: E2, E31 and H3
Keywords: business cycles, hours worked, tax shocks and technology shocks

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1 Introduction

The last decade has witnessed a lively debate on the sources of business cycles. Galí (1999), Francis and Ramey (2004) and Basu, Fernald and Kimball (2006) provide empirical evidence for US data that positive technological innovations give rise to a drop in aggregate hours worked. This finding leads to the rejection of the hypothesis of technology driven business cycles given the observed procyclicality of hours. However, the empirical results and their implications for business cycles theories have not remained unchallenged. Christiano, Eichenbaum and Vigfusson (2004a,b) cast doubt on Galì's (1999) assumptions regarding the trend stationarity properties of hours worked and on the exogeneity of Basu, Fernald and Kimball's (2006) measure of technology. They show that assuming stationary hours and taking into account possible endogeneity of Basu, Fernald and Kimball's (2006) technology estimates overturns the finding of a drop in hours worked. Fernald (2007) and Francis and Ramey (2009) question their arguments for stationarity of hours and show that, once low frequency movements are removed, hours worked again decrease after a positive technology shock. Fisher (2006) questions the validity of the identifying assumption that neutral technology shocks are the only source of fluctuations in the long-run level of labor productivity and argues that permanent investment-specific technology shocks also have permanent effects on labor productivity. He finds that allowing for investment-specific technology changes, productivity shocks account for a significant share of the in-sample variance of output and that hours worked increase after a permanent increase in investment specific technology shocks. However, Francis and Ramey (2009) show that these results depend on how one controls for demographic and sectoral shifts.

In this paper we focus on the role of permanent income tax changes on the measurement of permanent technology shocks and their effects on the economy. The potential importance of controlling for tax changes was raised earlier by Uhlig (2004a,b) who points out that changes in capital income tax rates may give rise to long lasting changes in labor productivity, therefore invalidating the standard identifying assumption for technology shocks. His analysis shows in particular how persistent changes in dividend taxes can have persistent effects on labor productivity as well as hours worked. Nonetheless, his empirical analysis falls short of demonstrating directly that controlling for changes in taxes leads to radically different results. Moreover, Galí (2004) refutes Uhlig's (2004a) criticism of the identifying assumption on the grounds that there is little correlation between taxes and identified technology shocks. Francis and Ramey (2005) consider a specification that includes capital income tax rates and find this does not alter the finding of a decrease in hours.

We go one step further than Uhlig (2004a,b) and demonstrate the empirical relevance of controlling for changes in taxes when estimating technology shocks and their effects. We begin by analyzing some of the consequences of permanent changes to income taxes in the context of a simple stochastic growth model. Permanent changes in income tax rates induce permanent changes in hours worked as well as in labor productivity. This leads to a violation of the standard long run identification strategy for technology shocks and, importantly, also implies a common stochastic trend in hours worked and labor productivity. We argue on the basis of the simple theoretical model for a vector error correction model (VECM) specification of labor productivity, hours worked and tax revenues as a way to correctly to account for a tax induced stochastic trend in the data.

Our empirical analysis uses quarterly post WWII US time series. In addition to allowing for additional sources of non-stationarity, our empirical strategy requires identification assumptions to disentangle technology shocks from tax shocks. Our approach follows Romer and Romer (2010) and Mertens and Ravn (2009) and relies on Romer and Romer's (2008) narrative account of historical US legislated federal tax liability changes, a subset of which are argued to be exogenous to business cycle conditions. We first confirm that Romer and Romer's (2008) tax shocks bring about significant permanent changes in labor productivity, output and hours worked, which under the assumption of exogeneity of the tax shocks casts doubt on the key identification assumption for technology shocks. We then show that orthogonalizing the data to the narrative tax shocks unambiguously changes the sign of the hours response to a long run identified productivity shock from negative to positive. Moreover, forecast error variance decompositions reveal that tax shocks as well as permanent productivity shocks are important contributors to business cycle fluctuations. These results are shown to be robust to adopting alternative measures of tax shocks and to distinguishing between anticipated and unanticipated tax changes.

The finding that controlling for tax shocks changes the sign of the hours response is however sensitive to assumptions made about stochastic trends. It does not obtain in specifications that assume stationarity of hours worked (such as a VAR with hours in levels) or in specifications that do not take into account cointegration (such as a VAR with hours in differences). We generate artificial data from the theoretical model and show that, as the importance of permanent shocks to tax rates increases, specifications that do not control for taxes and/or make erroneous assumptions about underlying stochastic trends produce negative responses of hours to productivity shocks in finite samples. The VECM specification that controls for tax shocks instead produces accurate estimates on average regardless of the importance of changes in taxes.

The remainder of the paper is organized as follows: Section 2 presents a simple real business cycle model with permanent tax shocks and discusses the implications for the time series properties of output and hours worked. Section 3 presents the empirical analysis of U.S. time series. Section 4 evaluates the small sample performance of different estimators in simulations of a theoretical model. Finally, Section 5 concludes.

2 Theory

Before turning to the empirical analysis, we start by introducing permanent exogenous changes in tax rates in a standard real business cycle model. Our aim is to bring out three insights. The first is that, as pointed out by Uhlig (2004a,b) and Francis and Ramey (2005), permanent changes in tax rates affect capital-labor ratios in the long run, therefore violating the long run identification assumption for a technology shock in Galí (1999). Second, with permanent tax shocks hours worked become nonstationary, which causes problems for empirical specifications that ignore low frequency movements in labor supply that are due to changes in tax rates. Finally, we use the model as motivation for our empirical specification in Section 3 and as a data generating process for simulations in Section 4 .

Households Household preferences are given by

$$\mathbb{E}_s \sum_{t=s}^{\infty} \beta^{t-s} \left(\ln c_t - \frac{\psi_t}{1+\kappa} n_t^{1+\kappa} \right) \tag{1}$$

where $\mathbb{E}_s x_t$ denotes the expectation of x_t given all information available at date $s \leq t$, $0 < \beta < 1$ is the subjective discount factor, $\psi_t > 0$ is a taste shock which follows a stationary stochastic process with mean ψ, $1/\kappa \geq 0$ is the Frisch labor supply elasticity, c_t denotes consumption in period t and n_t denotes hours worked. The household faces the flow budget constraints

$$c_t + k_{t+1} \leq (1-\tau_t)(w_t n_t + r_t k_t) + (1-\delta) k_t + m_t \ , \ \forall t \geq s \tag{2}$$

where k_t is the household's capital stock, k_s is given, $0 < \delta \leq 1$ is the depreciation rate, τ_t is the income tax rate, w_t is the real wage, r_t is the capital rental rate and m_t are lump-sum government transfers.

Firms Competitive firms produce output y_t using a Cobb-Douglas technology

$$y_t = k_t^{\alpha} (X_t n_t)^{1-\alpha} \tag{3}$$

where $0 < \alpha < 1$ is the elasticity of output with respect to the input of capital and X_t denotes the level of labor augmenting technology. Firms rent capital and labor from the households at given prices r_t and w_t and firm profits in period t are

$$\pi_t = y_t - r_t k_t - w_t n_t \tag{4}$$

Technology evolves according to

$$\ln(X_t / X_{t-1}) = \gamma_t^x = \gamma + \varepsilon_t^x \ , \ X_s \text{ given} \tag{5}$$

where $\gamma \geq 0$ and ε_t^x is mean zero random variable.

Government The government is in charge of fiscal policy. The income tax rate is subject to random but permanent changes, i.e.

$$\tau_t = \tau_{t-1} + \varepsilon_t^{\tau} \ , \ \ \tau_s \ \text{ given} \tag{6}$$

where ε_t^{τ} is a mean zero random variable. We assume that the only source of government expenditures are lump sum transfers m_t that adjust to ensure a balanced budget

$$m_t = \tau_t \left(w_t n_t + r_t k_t \right) \tag{7}$$

Equilibrium A competitive equilibrium is a sequence of allocations $(y_t, c_t, n_t, k_{t+1}, m_t)_{t=s}^{\infty}$ and a price system $(w_t, r_t)_{t=s}^{\infty}$ such that, given initial condition k_s, and processes for ψ_t, X_t and τ_t, (i) households maximize utility (1) subject to the budget constraints in (2), (ii) firms maximize profits (4) in every period, (iii) the government budget constraint in (7) is satisfied every period, and (iv) all markets clear.

Equilibrium sequences $(y_t,\ c_t,\ n_t,\ k_{t+1})_{t=s}^{\infty}$ are solutions to the following set of conditions:

$$\begin{aligned}
\psi_t n_t^{1+\kappa} &= (1-\alpha)\left(1-\tau_t\right)\frac{y_t}{c_t} && (8)\\
\frac{1}{c_t} &= \beta \mathbb{E}_t \left[\frac{1}{c_{t+1}} \left(\alpha \left(1-\tau_{t+1}\right) \frac{y_{t+1}}{k_{t+1}} + 1 - \delta \right) \right] && (9)\\
y_t &= k_t^{\alpha} \left(X_t n_t \right)^{1-\alpha} && (10)\\
y_t &= c_t + k_{t+1} - (1-\delta) k_t && (11)
\end{aligned}$$

The log of labor productivity can be expressed as

$$\ln\left(y_t/n_t\right) = \ln X_t + \frac{\alpha}{1-\alpha}\ln\left(k_t/y_t\right)$$

Equation (9) implies that a permanent increase in τ_t decreases the capital-output ratio and therefore labor productivity in the long run. In a deterministic setting, the capital-output ratio converges to

$$\frac{k}{y} = \frac{\alpha\beta(1-\tau)}{\gamma-\beta(1-\delta)}$$

which depends on the income tax rate τ. Thus, permanent technology shocks and permanent tax rate changes will both have effects on labor productivity in the long run. This invalidates the identifying assumption made by Galí (1999) that permanent neutral technology shocks are the only source of fluctuations in long run labor productivity. Moreover, there are also long run effects on hours worked through permanent changes in before and after tax wages and lifetime wealth. In a deterministic setting, hours worked converges to

$$n = \left(\frac{(1-\alpha)\,(1-\tau)\,/\psi}{1-(\gamma+\delta-1)\,k/y}\right)^{\frac{1}{1+\kappa}}$$

which depends negatively on the income tax rate τ. The recent literature has highlighted the importance of the stationarity properties of hours worked in estimating the effects of technology shocks. In practice, tax reforms are likely sources of low frequency changes in labor supply. Accounting for tax changes in the data may therefore be important not only for correct identification but also for the choice of specification of empirical models. To see this more clearly, we proceed by deriving an approximate linear representation of the data that will motivate our empirical specification in the next section.

Assume for now that there are no taste shocks, i.e. $\psi_t = \psi$ for all t. Define $\widetilde{c}_t = c_t/X_t$, $\widetilde{y}_t = y_t/X_t$, $\widetilde{k}_{t+1} = k_{t+1}/X_t$. Equilibrium sequences $\left(\widetilde{y}_t,\, \widetilde{c}_t,\, \widetilde{n}_t,\, \widetilde{k}_{t+1}\right)_{t=s}^{\infty}$ are solutions to the following set of conditions:

$$\psi n_t^{1+\kappa} = (1-\alpha)(1-\tau_t)\frac{\widetilde{y}_t}{\widetilde{c}_t} \tag{12}$$

$$\frac{1}{\widetilde{c}_t} = \beta \mathbb{E}_t\left[\frac{1}{\widetilde{c}_{t+1}}\left(\alpha(1-\tau_{t+1})\frac{\widetilde{y}_{t+1}}{\widetilde{k}_{t+1}} + \frac{1-\delta}{\gamma_{t+1}^x}\right)\right] \tag{13}$$

$$\widetilde{y}_t = \left(\widetilde{k}_t/\gamma_t^x\right)^{\alpha} n_t^{1-\alpha} \tag{14}$$

$$\widetilde{y}_t = \widetilde{c}_t + \widetilde{k}_{t+1} - \frac{1-\delta}{\gamma_t^x}\widetilde{k}_t \tag{15}$$

Consider a loglinear approximation of the equilibrium dynamics of the variables $\widetilde{y}_t$, $\widetilde{c}_t$, n_t, $\widetilde{k}_{t+1}$ and γ_t^x, τ_t by the linear system around a point $\widetilde{y}$, $\widetilde{c}$, n, $\widetilde{k}$ (defined in appendix) and γ, τ, yielding decision rules of the form

$$\widehat{k}_{t+1} = \phi_{kk}\widehat{k}_t - \phi_{kk}\varepsilon_t^x + \phi_{k\tau}\widehat{\tau}_t \tag{16}$$

$$\widehat{n}_t = \phi_{nk}\widehat{k}_t - \phi_{nk}\varepsilon_t^x + \phi_{n\tau}\widehat{\tau}_t \tag{17}$$

where hat variables denote log deviations of the point of approximation and the ϕ's are scalar coefficients and $\mid \phi_{kk} \mid < 1$. We wish to study the time series properties of a trivariate vector of observables that includes that the log growth rates of labor productivity $\Delta\ln(y_t/n_t)$, hours worked $\Delta\ln(n_t)$, and government tax revenues $\Delta\ln(T_t) \equiv \Delta\ln(\tau_t y_t)$. In appendix, we show that the decision rules in (16)-(17) yield the following moving average representation (omitting constants for brevity)

$$\begin{bmatrix} \Delta\ln(y_t/n_t) \\ \Delta\ln(n_t) \\ \Delta\ln(T_t) \end{bmatrix} = \left(\sum_{j=0}^{\infty} \Gamma_i L^i\right) \begin{bmatrix} \varepsilon_t^x \\ \varepsilon_t^\tau/\tau \end{bmatrix} = \Gamma(L) \begin{bmatrix} \varepsilon_t^x \\ \varepsilon_t^\tau/\tau \end{bmatrix} \tag{18}$$

where

$$\Gamma(L) = \begin{bmatrix} 1-\alpha(1-L)\left(\frac{1}{1-\phi_{kk}L}+\phi_{nx}-\frac{\phi_{nk}\phi_{kk}L}{1-\phi_{kk}L}\right) & \alpha\left(\frac{(1-\phi_{nk})\phi_{k\tau}L}{1-\phi_{kk}L}-\phi_{n\tau}\right) \\ (1-L)\left(\phi_{nx}-\frac{\phi_{nk}\phi_{kk}L}{1-\phi_{kk}L}\right) & \phi_{n\tau}+\frac{\phi_{nk}\phi_{k\tau}L}{1-\phi_{kk}L} \\ 1-\frac{\alpha(1-L)}{1-\phi_{kk}L}+(1-\alpha)(1-L)\left(\phi_{nx}-\frac{\phi_{nk}\phi_{kk}L}{1-\phi_{kk}L}\right) & 1+\alpha\frac{\phi_{k\tau}L}{1-\phi_{kk}L}+(1-\alpha)\left(\phi_{n\tau}+\frac{\phi_{nk}\phi_{k\tau}L}{1-\phi_{kk}L}\right) \end{bmatrix}$$

and L is the lag operator.

This representation permits the Beveridge-Nelson decomposition

$$\begin{bmatrix} \ln(y_t/n_t) \\ \ln(n_t) \\ \ln(T_t) \end{bmatrix} = \begin{bmatrix} \ln(y_0/n_0) \\ \ln(n_0) \\ \ln(T_0) \end{bmatrix} + \gamma_0 + \Xi \sum_{j=0}^{t-1} \begin{bmatrix} \varepsilon_{t-j}^x \\ \varepsilon_{t-j}^\tau/\tau \end{bmatrix} + \Xi^*(L) \begin{bmatrix} \varepsilon_t^x \\ \varepsilon_t^\tau/\tau \end{bmatrix} \tag{19}$$

where

$$\Xi^*(L) = \sum_{j=0}^{\infty}\left(-\sum_{i=j+1}^{\infty}\Gamma_i\right)L^j\ ,\ \ \gamma_0 = \sum_{j=t}^{\infty}\left(-\sum_{i=j+1}^{\infty}\Gamma_i\right)\begin{bmatrix} \varepsilon_{t-j}^x \\ \varepsilon_{t-j}^\tau \end{bmatrix}\ ,\ \ \Xi = \begin{bmatrix} 1 & \alpha\left(\frac{(1-\phi_{nk})\phi_{k\tau}}{1-\phi_{kk}}-\phi_{n\tau}\right) \\ 0 & \left(\phi_{n\tau}+\frac{\phi_{nk}\phi_{k\tau}}{1-\phi_{kk}}\right) \\ 1 & 1+\alpha\frac{\phi_{k\tau}}{1-\phi_{kk}}+(1-\alpha)\left(\phi_{n\tau}+\frac{\phi_{nk}\phi_{k\tau}}{1-\phi_{kk}}\right) \end{bmatrix}$$

Equation (19) decomposes the time series into a sum of initial conditions (first two terms), a bivariate random walk component (third term) and a bivariate stationary process (last term). The matrix Ξ captures the long run effects on the variables of the structural shocks. Since $\text{rank}(\Xi) = 2$, it is clear that permanent shocks to taxes introduce a second stochastic trend in the data. As the first element in the second column of Ξ is generally not zero, permanent tax shocks affect labor productivity in the long run. As the second element of the second column in Ξ is in general not zero, permanent tax shocks also introduce a stochastic trend into hours worked. The latter implies that an appropriate empirical specification should allow for nonstationary hours. Given the focus on the role of taxes it is compelling to include data on tax revenues, which in practice requires one additional shock to avoid stochastic singularity. We assume this additional shock has no long run impact on either labor productivity or hours worked. It therefore also does not affect tax revenues in the long run, as is the case for the stationary taste shock ψ_t in the theoretical model. In that case, the long run impact matrix Ξ has deficient rank and there is a cointegration relationship described by the null space of Ξ'. A vector ζ is a cointegrating vector if:

$$\Xi'\zeta = 0$$

However, a vector stochastic process with cointegrating variables does not admit a pure VAR representation in first differences, which is why we will adopt a vector error correction specification (VECM). For the null space to be of the correct dimension one, we need to include variables in the system that ensure that $\text{rank}(\Xi) = 2$. One reason why tax revenues is a good choice for the third variable in the specification is that the long run impact on tax revenues of permanent tax changes is likely to be of the opposite sign as the impact on the other variables.

Discussion The analysis above assumes that a tax change gives rise to a simultaneous change in both labor income and capital income tax rates. Alternatively, one might consider changes in only one of these two tax rates. In a simple model like the one studied above, permanent shocks to labor income taxes alone affect hours worked but leave labor productivity unchanged in the long run. Permanent changes in capital income taxes instead have effects similar to those that we derived above. The apparent differential impact of changes in labor income taxes and capital income taxes is not general and results from many simplifying assumptions. In settings with educational choices, human capital accumulation or other sources of endogenous changes in labor productivity (such as learning by doing), permanent changes in labor income taxes can affect the long run level of labor productivity through the impact on the incentive to accumulate skills. In particular, increases in labor income taxes lower the return on skills and therefore decrease measured labor productivity as long as skills are productive. Similarly, changes in labor income taxes can affect the retirement decisions of older workers and this participation choice may in turn affect labor productivity if skills are accumulated over the lifecycle.

An alternative mechanism that can induce a link between labor income taxes and labor productivity is the government budget constraint. If the government adjusts capital income taxes to changes in the primary deficit to ensure long-run solvency (or, more extremely, to balance the budget period-by-period), then, for a given level of government spending, a cut in labor income taxes can lead to an increase in (future) capital income taxes, which affects the long-run level of labor productivity.[1]

In summary, the model above highlights that permanent changes in taxes invalidate the standard identifying assumption for productivity shocks and induce a common stochastic trend in hours worked and labor productivity. While simple models suggest only capital income taxes have long

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[1] Uhlig (2004a) allows for the reverse of this mechanism in his analysis of the hours-technology relationship. In particular, he assumes that there are exogeneous changes in capital income taxes but that these feed into labor income taxes through the government budget constraint. Through this mechanism, he finds that persistent cuts in capital income taxes can bring about persistent increases in labor productivity and persistent declines in hours worked.

run effects on labor productivity, in more general settings permanent changes in labor income tax rates can affect hours worked as well as labor productivity in the long run.

3 Empirical Analysis

In this section we estimate structural VARs and VECMs in which, using the insights from the previous section, we impose identifying assumptions and cointegration relationships that allow for the estimation of the impact of technology shocks while controlling for tax shocks. As a side product, this also allows us to estimate the impact of tax changes.

The empirical analysis uses U.S. quarterly time series for the sample period 1948:Q1-2007:Q4 on labor productivity and hours worked from Francis and Ramey (2009). The Francis-Ramey time series on per capita hours worked (denoted by n_t) is obtained by dividing an average hourly worked estimate corrected for demographic changes by the civilian population ages 16 and above. We also use data on U.S. tax revenues from the BEA.[2] Figure 1 plots the time series used.

Our approach to identifying tax changes makes use of the narrative account of U.S. federal tax liability changes provided by Romer and Romer (2008). We study only those tax changes that Romer and Romer (2008) classify as "exogenous due to long-term growth objectives" or exogenous due to "deficit concerns". The former of these are tax changes that were introduced with no explicit concerns about the current state of the economy while the latter are tax changes introduced

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[2] The hours worked (demographically adjusted average weekly hours, *avgwkhrs_adj*) and real GDP series (*rgdp*) is from Francis and Ramey (2009) and was downloaded on 04/20/2010 at *http://www.econ.ucsd.edu/~vramey/research/Francis-Ramey_JMCB_Data_09.xls*. Tax revenues are seasonally adjusted current tax receipts (NIPA Table 3.2, line 2) divided by the GDP deflator (NIPA Table 1.1.4, line 1) and by total noninst. population aged 16+ (from Francis and Ramey (2009)).

to address inherited budget deficits. The tax shocks are depicted in Figure 2. This approach has the advantage that tax shocks can be treated as observable and therefore easily controlled for but rests crucially on the assumption that the tax liability changes identified by Romer and Romer (2008) can be assumed exogenous. Mertens and Ravn (2009) and Favero and Giavazzi (2010) test this assumption formally and show it cannot be rejected.

3 .1 A Two-Dimensional VAR

As a first step we replicate existing estimates of the impact of permanent productivity shocks using the conventional long run restrictions without controlling for tax changes. We estimate the following bivariate VAR:

$$A(L)\, z_t = u_t \tag{20}$$

where $A(L) = I_2 - A_1 L - .. - A_p L^p$ is an p-order lag polynomial and z_t is the vector of observables which consists of the first difference of (the logarithm of) labor productivity, $\Delta \ln(y_t/n_t)$, and either the level or first difference of (the logarithm of) hours worked, i.e. $\ln(n_t)$ or $\Delta \ln(n_t)$. u_t is the vector of reduced form errors.[3] These are related to the structural shocks through the relationship:

$$u_t = Be_t \tag{21}$$

where e_t denotes the vector of orthogonal structural shocks. We identify the technology shocks by imposing Galì's (1999) identifying assumption that only technology shocks have a long run impact on the level of labor productivity. Let $\Xi = A(1)^{-1}B$ denote the long run total impact matrix and Σ_u

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[3] For notational simplicity we exclude deterministic terms. However, all our estimations include constant terms.

the variance-covariance matrix of u_t. Productivity shocks are identified through the restriction

$$B = A(1)\text{chol}\left[A(1)^{-1}\Sigma_u(A(1)^{-1})'\right]$$

Panel (a) of Figure 3 shows the estimated impulse response functions for $p = 4$ of labor productivity, output per capita, and hours worked to a one standard deviation productivity shock when we enter hours worked in differences for a forecast horizon of 10 years. The shaded areas show 68 percent and 95 percent confidence intervals computed with a nonparametric bootstrap. Panel (b) of Figure 3 illustrates the impulse responses when the VAR includes the level of hours worked.

The results confirm the findings of Francis and Ramey (2009). Regardless of the stationarity assumptions made on hours worked, a permanent technology shock gives rise to a temporary drop in hours worked while output and labor productivity rise permanently. The two dimensional specifications therefore cast doubt on the importance of technology shocks as a source of business cycle fluctuations.

3 .2 A Three-Dimensional VECM Specification

We now consider a slightly more general specification where the vector of observables includes also tax revenues. We specify the empirical model as a vector error correction model:

$$\Delta z_t = \alpha\beta' z_{t-1} + C(L)\Delta z_{t-1} + u_t \tag{22}$$

where $z_t = [\ln(y_t/n_t), \ln n_t, \ln T_t]'$. $C(L) = C_0 + C_1 L + .. + C_p L^p$ is a p-order lag polynomial, α is a $3 \times r$ loading matrix, β is a $3 \times r$ cointegration vector and the rank of $\alpha\beta'$ is equal to r (the cointegration rank). Formal tests of cointegration rank consistently reject the null of $r = 0$, which would correspond to running a VAR with all variables in first differences.[4] The tests proved inconclusive on whether $r = 1$ or $r = 2$.[5] Motivated by the discussion in the previous section, we impose one cointegrating relationship $r = 1$, which means we allow for two shocks that have potentially permanent effects on all variables, including hours worked, and one shock that is restricted to have only transitory effects. As before we assume that u_t is linked to the structural shocks e_t through (21). The long run total impact matrix in the VECM is

$$\Xi = \left(\beta_\perp \left[\alpha'_\perp \left(I_n - C(1)\right)\beta_\perp\right]^{-1} \alpha'_\perp\right) B$$

where it follows, due to the cointegration restriction, that $\operatorname{rank}(\Xi) = 2$. In this equation $\alpha_\perp$ and $\beta_\perp$ denote the orthogonal complements of α and β, respectively. The last column of this matrix, which corresponds to the impact of the transitory shock, is equal to the null vector. The productivity shock is again identified as the only shock with a long run impact on the level of labor productivity. We estimate the VECM with $p = 4$.

The results are illustrated in Figure 4. A positive permanent productivity shock gives rise to a permanent increase in output and in labor productivity. The shapes and size of these responses are very similar to those of the bivariate VARs in (20) when we entered hours worked in differences and not very different from the specification that entered hours worked in levels. As is the case in the VARs, hours worked fall in response to a productivity shock.[6]

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[4] We used the Johansen (1995) trace test and the Saikkonen and Lutkepohl (2000) test.

[5] The test statistics depend on the lag length p and the specification of the deterministic terms.

[6] We also estimated trivariate VARs that included tax revenues, both with hours in first differences an in levels, and found very similar results.

We believe, however, that one reason to be skeptical about these results is the estimated impact of productivity shocks on tax revenues. Figure 4 shows that a positive technological innovation gives rise to an immediate drop in tax revenues of close to 1 percent despite the output increase. The standard errors of the impulse responses are quite large so one cannot reject with great confidence that tax shocks have no impact on tax revenue. The point estimates, however, indicate a drop in tax revenues for a prolonged period stretching up to 3 years after the increase in productivity. To us, such a countercyclical response of tax revenues seems quite implausible. As permanent tax cuts are likely to be picked up as positive productivity shocks by the long run identification assumption, we proceed by controlling for changes in taxes.

3 .3 Technology Shocks - Hours Worked Redux and Tax Changes

We estimate the following extended VECM model:

$$\Delta z_t = \alpha\beta' z_{t-1} + C(L)\Delta z_{t-1} + D(L)\varepsilon_t^{RR} + u_t \tag{23}$$

where $D(L) = D_0 + D_1 L + ..D_m L^m$ is an m-order lag polynomial and ε_t^{RR} denote Romer and Romer's (2008) tax shocks, which are narrative measures of exogenous changes in tax revenues due to legislative changes (as percentage of GDP). The key aspect of this way of controlling for tax changes is that we can treat the tax shocks as observable when estimating technology shocks and their impact. As Romer and Romer (2010) and Mertens and Ravn (2009), we therefore include the polynomial $D(L)$ to explicitly allow for dynamics of the adjustment in tax rates. This specification is shown in Section 4 to work very well in small sample simulations. Romer and Romer (2008) document that almost all of the recorded tax changes labeled exogenous were indeed legislated to be permanent. Below, we investigate robustness to using different tax shock measures, including dropping a few explicitly temporary tax changes. Since the tax shocks are assumed observable, we employ the same long run identifying assumption as before on the presumption that, by conditioning on the narrative tax shocks, the unexplained long run variation in labor productivity is now orthogonal to any (major) permanent and exogenous changes in taxes.

The specification in equation (23) does not make a distinction between tax liability changes that affect labor income taxes and tax liability changes that relate mainly to capital income taxes. As we have discussed earlier, this might potentially be a problem. Nonetheless, if this concern is serious, we would expect tax changes to have small and very uncertain effects on hours and labor productivity. We let the data speak for itself on the relevance of this issue: Figure 5 plots the response of the variables to a one percent decrease in average taxes for $m = 12$, which sets off large adjustments in the main macroeconomic aggregates. According to our estimates, labor productivity rises permanently by approximately 1 percent while output rises by 2 percent at high confidence levels. The apparent long run effect on labor productivity confirms that permanent tax changes are likely to invalidate the conventional long run restriction. A tax shock also affects the level of hours worked in the long run, albeit at lower confidence levels. Hours worked increases by 1.5 percent at the peak, which occurs 3 years after the tax cut, and then stabilizes at a level corresponding to a one percent long run increase. Finally, we find that tax revenues decrease significantly in the short run by almost 4 percent, and gradually recover over time with a long run effect that is not significantly different from zero.

The estimated response to the Romer and Romer (2008) tax shocks suggest that controlling for changes in taxes over time could be important for interpreting innovations in productivity as technology shocks. Figure 6 illustrates the impulse responses to a productivity shock in the VECM model that includes the tax shock measure. As before, we find that a positive shock is associated with a permanent increase in labor productivity and aggregate output. However, the response of hours worked is surprisingly different. We now find, in contrast to Galí (1999) and Francis and Ramey (2005, 2009), that a positive productivity shock brings about a highly significant increase in hours worked in the short run. The estimates imply a maximum increase of 0.6 percent about one year after the shock. Thereafter, hours worked returns slowly towards its original level with the increase being significantly positive for 2 years at the 95 percent level and for 4 years at the 68 percent level. At long forecast horizons, the estimates imply no significant impact of technology shocks on hours worked. This response of hours worked seems much more consistent with standard neoclassical business cycle models.

It is also noteworthy that the estimates for the impact of productivity shocks on tax revenues are different from those in the VECM that does not include the tax shocks, shown in Figure 4. We now find that a positive innovation to technology gives rise to an increase in government tax revenues that is quite large. One year after an innovation in productivity, tax revenues are estimated to increase by around 3 percent. Tax revenues remain significantly above trend up to 4.5 years after the shock. These estimates are now in line with the standard intuition of procyclical tax revenues.

Clearly, including the Romer and Romer (2008) tax shocks has strong implications for estimating the response to long run identified productivity shocks. In order to gain some further understanding of our results, Figure 7 plots the counterfactual path of hours worked driven by the tax shocks only (left panel) as well as the tax detrended path of hours (right panel). There are three episodes where, according to our estimates, changes in taxation have considerably affected long run trends in labor supply. In the 1960s, primarily through the Kennedy tax cuts, labor supply experienced an increase that persisted throughout the 1970s. The early Reagan tax reforms caused a second trend increase in labor supply in the mid 1980s that was reversed by subsequent tax increases under Reagan, Bush I and Clinton, lowering the trend labor supply in the 1990s back to pre-Kennedy levels. The Bush II tax cuts again increased trend labor supply in the early 2000s. Figure 8 shows the estimated smoothed productivity shocks in the VECMs with and without controlling for tax changes. The correlation between the two series is 0.61, indicating that including the tax shocks substantially changes the estimated path of exogenous changes in productivity growth. The most remarkable differences occur during the recession of 1970, where the specification with taxes detects a deterioration in productivity growth instead of an improvement; the mid 1980s, where the tax specification finds persistent low productivity growth; the second half of the 1990s, for which the tax specification detects repeated high productivity growth rates; and the recession in the early 2000s, during which low productivity growth is detected when taking into account the low frequency movements due to taxes.

Given these findings, a natural question is whether technology shocks account for a substantial amount of fluctuations of the macroeconomic aggregates. Figure 9 plots the counterfactual path of output growth driven by only productivity shocks in the VECM specifications without and with the tax shocks (panel (a) and panel (b) respectively). The results are very clear. When we do not control for tax shocks, the counterfactual path for output growth that is due to technology shocks bears no or little resemblance to the observed path of output growth in the U.S. Instead, when we do control for tax changes, the path of output induced by technology shocks is closely related to actual output growth and technology shocks account for a significant proportion of the variance of output growth. According to our estimates, the correlation between observed output growth and the counterfactual path of output growth driven only by productivity rises to 0.78 from 0.40 when the tax shocks are included. To further quantify the contribution of the productivity and tax shocks we compute variance decompositions for the h-step ahead forecast errors:

$$f_{t,h} = z_{t+h} - E\left(z_{t+h}|\Omega_t\right) \tag{24}$$

where Ω_t denotes the econometrician's information set at date t and the conditional expectation are forecasts from the identified VECM. Because of the nonstandard distribution of the tax shocks, we compute the variance contributions through 100,000 bootstrap simulations (a high number is required because of the many zero observations in the tax shock series).

Figure 10 displays the proportion of the forecast error variance of labor productivity, output, and hours worked that is accounted for by permanent productivity shocks, tax shocks, and by the remaining other shocks in the VECM which we aggregate together under the heading "other". Productivity shocks account for around 60-70 percent of the forecast error variance of labor productivity with the fraction being highest at short forecast horizons, 50-55 percent of the forecast error variance of output, and 0-25 percent of the forecast error variance of hours worked. For comparison, in the VECM without tax shocks we found that productivity shocks explain only about 10-15 per cent of the forecast error variance of output. The estimated variance contribution of productivity shocks in the VECM with the Romer and Romer (2008) tax shocks is substantially greater than found by Galí (1999) and imply that technology shocks are an important source of fluctuations in output. Fluctuations in hours worked are less heavily influenced by technology shocks.

Tax shocks are also a relevant source of fluctuations in the macroeconomic aggregates. According to our estimates, changes in taxes account for around 10 percent of the forecast error variance of output and labor productivity and 5 percent of the variance of fluctuations in hours worked. These numbers are fairly constant over the forecast horizons (apart from very short horizons). Thus, in combination, technology shocks and tax shocks account for the bulk of variation in output and labor productivity (60 and 70 percent, respectively) and for a good share of the variation of hours worked (around 30 percent).

In summary, our analysis shows that once one controls for Romer and Romer's (2008) tax shocks in the VECM, long run identified productivity shocks give rise to an increase in hours worked and productivity and tax shocks together account for a substantial fraction of the variance of output and labor productivity. Our results therefore challenge the conclusions reached by Galí (1999), Francis and Ramey (2005, 2009) and Basu, Fernald and Kimball (2006) regarding the importance of technology shocks as a source of business cycle fluctuations. We stress, however, that the finding that including the RR tax shocks changes the sign of the hours response does not generalize to the VAR specifications. When we adopt a difference specification for hours, the hours response remains significantly negative. In the level specification, the hours response becomes insignificant at the 68% confidence level when we include the tax shocks. The simulations in Section 4 reveal a similar pattern of differences across specifications in artificial data generated from the RBC model.

3 .4 Robustness

The specification in equation (23) controls for tax shocks as measured by Romer and Romer (2008). Elsewhere we have argued that it may be important to distinguish between anticipated and unanticipated changes in taxes as many changes in taxes are preannounced. In this section we examine whether these considerations are important for our results. We also examine whether the results are sensitive to eliminating some tax changes that were explicitly meant to be temporary, and to the general motivation for the tax changes.

Anticipated vs. Unanticipated Tax Changes We first examine whether our results depend on the timing of the tax shocks. Changes in taxes are often legislated and/or announced well ahead of their implementation, see Mertens and Ravn (2009). If agents react to tax announcements ahead of their implementation, the econometric estimates should take this into account. Failure to do so leads to misidentification and can create serious problems for VAR and VECM estimators, see Leeper, Walker and Yang (2008) and Mertens and Ravn (2010).

Here we follow Mertens and Ravn (2009) and make a distinction between anticipated and unanticipated changes in taxes based on dates of enactment and implementation. We assume that tax changes that were implemented within a 90 days window of enactment are unanticipated while tax changes with a longer implementation lag are assumed to be anticipated. Minor changes in the width of this window have little impact since the empirical distribution of the implementation lag is twin-peaked with most tax changes have either a very short implementation lag or an implementation lag of several quarters. Around half of the tax liability changes have implementation lags longer than 90 days (therefore being categorized as anticipated) and the median implementation lag is 6 quarters.

As in Mertens and Ravn (2009) we measure anticipated tax shocks in terms of their remaining implementation lag. We let $\varepsilon_{t,i}^{RR,a}$ denote the sum of all tax changes that have been announced at date t or earlier that are to be implemented at date $t+i$, $i \geq 1$. We set the maximum implementation lag equal to 2.5 years since longer lags lead to very few observations at long implementation lags. As before, tax shocks are measured as a ratio of nominal GDP at the implementation date. Similarly, we let $\varepsilon_t^{RR,u}$ denote the unanticipated changes in tax liabilities as a percent of GDP at the implementation date. We then estimate the following VECM model:

$$\Delta z_t = \alpha\beta' z_{t-1} + C(L)\Delta z_{t-1} + D(L)\varepsilon_t^{RR,u} + F(L)\varepsilon_{t,0}^{RR,a} + \sum_{i=1}^{q} G_i \varepsilon_{t,i}^{RR,a} + u_t \tag{25}$$

where $F(L)$ as $D(L)$ is an m-order lag polynomial, and q denotes the maximum implementation lag. We use $m = 12$ and $q = 6$.

In Figure 11 we show the estimated impulse response functions to a one standard deviation productivity shock. The estimates are very similar to those in Figure 6 where we ignored the timing issues. The finding of a positive response of hours worked remains intact. Figure 12, panel (a) reports the impulse responses of labor productivity, output and hours to an unanticipated 1 percent tax cut in tax liabilities, whereas panel (b) shows the responses to an anticipated tax shock that is announced 6 quarters prior to its implementation. The results are similar to those estimated by Mertens and Ravn (2009) using a very different specification of the time series process for the vector of observables. The announcement of a future tax cut leads to a decline in aggregate output which is reversed only when the tax cut is actually implemented. The pre-implementation slump is around 1 percent. After the tax cut is implemented, aggregate output rise to around 2 percent above trend. Similarly, we find a pre-implementation slump in aggregate hours worked which peaks at a level corresponding to a 1 percent drop 4 quarters before the tax cut is implemented. Once the tax cut is implemented, hours worked rise approximately 1.5 percent above trend. These estimates are similar in shapes and sizes to the estimates in Mertens and Ravn (2009) but associated with larger standard errors. This is most likely due to the greater number of reduced form coefficients estimated. Finally, we note that the impact of anticipated tax shocks on labor productivity is relatively muted and estimated with a lot of uncertainty.

Tax Duration and Motivation The tax series that we have studied includes a few instances of explicitly temporary tax liability changes, although some actually were later extended or even made permanent. To establish that the results are robust to eliminating these temporary tax changes, we re-estimate equation (23) excluding all temporary tax changes. In addition, Romer and Romer (2008) distinguish between tax changes that were motivated either by a desire to affect long run growth or by long run budgetary considerations. We therefore also re-estimate equation (23) using only the long run growth driven tax changes.

Figure 13 shows the response to a productivity shock of output, labor productivity and hours worked from these two alternative specification in comparison with the baseline case. The figure shows that the results are robust to using these alternative tax shock measures. The path of labor productivity is basically identical across the three different specification. The responses of output and hours worked in the baseline case and when we focus on ideologically founded tax changes are also as good as identical. We find marginally smaller increases in output and hours worked when we eliminate tax changes meant to be temporary. Nonetheless, our previous conclusions are not affected in any significant way.

4 A Small Sample Perspective

In this section we provide Monte Carlo evidence to support our empirical specification and identification strategy. The main objective of the simulations is to illustrate how alternative time series models, including VAR specifications with hours in levels or differences, may fail in the presence of permanent tax shocks and produce responses of hours worked with the wrong sign. Even though the simulation results should be regarded with care as they are derived from a specific model setting, we believe they are informative about the interpretation of our empirical findings. One particular concern that has arisen in the literature regards the poor small sample properties of long run identified structural time series models. Chari, Kehoe and McGrattan (2008) argue that small sample problems insert sufficient bias to prevent structural VARs from providing any guidance for evaluating economic theory. The simulation experiments in this section also examine the extent of this concern for our tax augmented VECM specification.

We calibrate the model of Section 2 and use it to generate artificial data to which we apply various time series models. The stochastic processes for technology shocks, tax shocks and leisure taste shocks are parameterized by:

$$\begin{aligned}
\ln(X_t/X_{t-1}) &= \gamma+\varepsilon_t^x \ , \ \ \varepsilon_t^x \sim N(0,\sigma_x^2) && (26)\\
\tau_t &= \tau_{t-1}+\varepsilon_t^\tau \ , \ \ \varepsilon_t^\tau \sim N(0,\sigma_\tau^2) && (27)\\
\ln\psi_t &= (1-\rho_\psi)\ln(\psi)+\rho_\psi \ln\psi_t+\varepsilon_t^\psi \ , \ \ \varepsilon_t^\psi \sim N(0,\sigma_\psi^2) && (28)
\end{aligned}$$

Most of the parameters of the model are taken from the estimates of Chang, Gomes and Schorfheide (2002) and are as follows: $\alpha = 0.6563$, $\beta = 0.9934$, $\gamma = 0.0040$, $\delta = 0.0226$, $\kappa = 1/1.3088$, $\rho = 0.9442$, $\sigma_x = 0.0116$, $\sigma_\psi = 0.0089$. We set the initial tax rate equal to $\tau = 0.30$ which is close to the relevant number for the US.

We generate 10,000 artificial samples of 240 observations each for a specific value of the standard deviation of tax changes σ_τ. We consider values for σ_τ ranging from 0.001 to 0.02. Evidently, as σ_τ increases, permanent tax shocks play a larger role in fluctuations of all variables. In each of the artificial samples we estimate the impulse responses to a one standard deviation long run identified technology shock in different trivariate time series models of labor productivity, hours worked and tax revenues: (1) a VAR with hours in levels (2) a VAR with hours in first differences (3) a VECM with one cointegration relationship. We also estimate all three specifications with and without including artificial Romer and Romer tax shocks. The RR tax shocks in the artificial samples are

$$\varepsilon_t^{RR} = \varepsilon_t^{\tau} + \varepsilon_t^{me} \ \ , \ \ \varepsilon_t^{me} \sim N(0, 0.01^2)$$

where ε_t^{me} is a measurement error. For each value of σ_τ, we average the impulse responses over the 10,000 samples.

Figure 14 shows the first period response of hours averaged across simulations for different time series models as a function of the variance of the (true) tax innovation. We assume a lag length of $p = 4$ quarters for all models. For the specifications that include the tax shocks, we set $m = 12$ as before. Figure 14 also shows the true theoretical response of hours worked which is a 0.1% increase in hours worked upon impact. Before we compare performance across specifications, we note that none of the reduced form time series models captures the full structure of the infinite order moving average representation in (18). All specifications necessarily condition only on a finite history of observables, which may not lead to accurate estimates of the infinite sum of autoregressive coefficients required for long run identification. By varying the volatility of permanent tax shocks, we wish to highlight the additional potential sources of bias that arise, on the one hand because of erroneous assumptions regarding stochastic trends in the data, on the other hand because of the failure of the identification assumption.

In Figure 14, the main finding is that the VECM with RR tax shocks (as in equation (23)) performs well on average regardless of the variance of taxes, whereas all other specifications produce estimates with erroneous signs for many values of σ_τ. The VARs that enter hours worked in differences, perform poorly for all values of σ_τ. The main reason is that, regardless of the importance of permanent tax changes, the data generating process never permits a difference VAR specification because of cointegration. For the case where the *RR* shocks are omitted and as σ_τ becomes larger, not controlling for tax shocks leads in addition to erroneous identification and much larger bias. The VARs that include hours in levels fare relatively well when σ_τ is low and permanent tax shocks are not too important. This is because both identification and specification errors due the permanent effects of tax shocks are relatively mild for low σ_τ. Nonetheless, they tend to somewhat exaggerate the positive response of hours worked to technology shocks. For sufficiently volatile tax shocks, however, the level VARs produce a response of hours that has the wrong sign both with and without including the RR tax measures, although the bias tends to be smaller when the RR tax shocks are included. Both VECMs produce on average accurate estimates when σ_τ is low. The VECM that does not control for tax innovations, however, again produces responses that are of the wrong sign when σ_τ is sufficiently large. This is because despite the appropriate treatment of stochastic trends in the data, the long run identification assumption fails to disentangle technology from tax shocks. The only specification that produces estimates that are robust to different values of σ_τ is the VECM that includes the RR tax shocks. We repeated this analysis for the response of hours worked at the one year horizon and found essentially identical results that we therefore do not report.

These simulation results support our claim that the structural VECM specification in equation (23) is more likely to produce reliable estimates of the impact of technology shocks on hours worked. It is reassuring that how the impact of including the tax shocks varies with stationarity assumptions can relatively easily be replicated in model simulations. The results provide an explanation for why previous contributions to the literature have estimated a negative impact of technology shocks on hours worked.

5 Conclusion and Future Research

In this paper we argue for controlling for permanent tax shocks when estimating the impact of technology shocks through long run restrictions. Permanent changes in taxes induce nonstationarity in hours worked and invalidate the standard identifying assumption for technology shocks. Including the Romer and Romer (2008) tax liability shocks in a technology VECM overturns the negative response of hours to a productivity shocks in US post war time series. This finding is robust to alternative tax shock measures but depends importantly on assumptions about underlying stochastic trends. This dependence can however easily be replicated in simulations of a standard business cycle model.

Our analysis lends itself to several extensions and to further robustness analysis. First, we have not considered the impact of investment specific technology shocks, which Fisher (2006) argues are also relevant sources of long run changes in labor productivity. It would therefore be interesting to extend the empirical models to allow for investment specific technology shocks. Second, it would be potentially important to derive more precise estimates of changes in tax rates. The Romer and Romer (2008) measure lumps together different types of taxes and although changes in different types of taxes are correlated, a further breakdown for instance into income and payroll taxes may be useful. Finally, the Romer and Romer (2008) tax measure may potentially suffer from endogeneity problems. We have elsewhere argued that this does not seem to be a serious problem (see Mertens and Ravn (2009)) but the issue deserves further attention in future research.

References

Basu, Susanto, John G. Fernald, and Miles S. Kimball, 2006, “Are Technology Improvements Contractionary?”, American Economic Review 95, pp. 1418-1448.

Chang, Yongsung , Joao F. Gomes and Frank Schorfheide, 2002, “Learning-by-Doing as a Propagation Mechanism”, American Economic Review 92(5), pp. 1498-1520

Chari, V.V., Patrick J. Kehoe and Ellen R. McGrattan, 2008, “Are Structural VARs with Long Run Restrictions Useful in Developing Business Cycle Theory?”, Journal of Monetary Economics 55(8), pp. 1337–1352.

Christiano, Lawrence, Martin Eichenbaum and Robert Vigusson, 2004a, “What Happens After A Technology Shock?”, mimeo, Northwestern University.

Christiano, Lawrence, Martin Eichenbaum and Robert Vigusson, 2004b, “The Response of Hours to a Technology Shock: Evidence Based on Direct Measures of Technology”, Journal of the European Economic Association 2(2/3), pp. 381–395.

Favero, Carlo, and Francesco Giavazzi, 2010, “Reconciling VAR-based and Narrative Measures of the Tax Multiplier”, manuscript, Bocconi University.

Fernald, John G., 2007, “Trend Breaks, Long-Run Restrictions, and Contractionary Technology Improvements”, Journal of Monetary Economics 54(8), pp. 2467–2485

Fisher, Jonas, 2006, “The Dynamic Effects of Neutral and Investment-Specific Technology Shocks”, Journal of Political Economy 114, pp. 413—52.

Francis, Neville, and Valerie A. Ramey, 2004, “The Source of Historical Economic Fluctuations: An Analysis Using Long-Run Restrictions”, NBER International Seminar on Macroeconomics, pp. 17–49.

Francis, Neville , and Valerie A. Ramey, 2005. Is the Technology-Driven Real Business Cycle Hypothesis Dead? Shocks and Aggregate Fluctuations Revisited”, Journal of Monetary Economics 52(8), pp. 1379–1399

Francis, Neville , and Valerie A. Ramey, 2009, “Measures of per Capita Hours and Their Implications for the Technology-Hours Debate”, Journal of Money, Credit and Banking, 41(6): pp. 1072–1097.

Galí, Jordi, 1999, “Technology, Employment and the Business Cycle: Do Technology Shocks Explain the Business Cycle?”, American Economic Review 89, pp. 249–271.

Galí, Jordi, 2004, “On the Role of Technology Shocks as a Source of Business Cycles: Some New Evidence”, Journal of the European Economic Association 2(2-3), pp. 372–80.

Johansen, Søren, 1995,“Likelihood-based Inference in Cointegrated Vector Autoregressive Models", Oxford University Press, Oxford.

Leeper, Eric M., Todd B. Walker and Shu-Chun Susan Yang, 2008, "Fiscal Foresight: Analytics and Econometrics", manuscript, Indiana University.

Mertens, Karel and Morten O. Ravn, 2009, "Empirical Evidence on the Aggregate Effects of Anticipated and Unanticipated U.S. Tax Policy Shocks", CEPR Discussion Paper no. 7370.

Mertens, Karel and Morten O. Ravn, 2010,"Measuring the Impact of Fiscal Policy in the Face of Anticipation: A Structural VAR Approach", Economic Journal, 120(3), pp. 393–413.

Romer, Christina D., and David H. Romer, 2008, "A Narrative Analysis of US Postwar Tax Changes", University of California, Berkeley, manuscript.

Romer, Christina D., and David H. Romer, 2010, "The Macroeconomic Effects of Tax Changes: Estimates Based on a New Measure of Fiscal Shocks", American Economic Review 100(3), pp. 763–801.

Saikkonen, Pentti, and Lutkepohl, Helmut, 2000, "Testing for the Cointegrating Rank of a VAR process With an Intercept", Econometric Theory 16, pp. 373–406.

Uhlig, Harald, 2004a, "Comment on: The Source of Historical Economic Fluctuations: An Analysis Using Long-Run Restrictions, by Francis Neville and Valerie A. Ramey", NBER International Seminar on Macroeconomics, pp. 50–69.

Uhlig, Harald, 2004b, "Do Technology Shocks Lead to a Fall in Total Hours Worked?", Journal of the European Economic Association 2(2-3), pp. 361–371.

A Point of Approximation

The constants $\widetilde{y}$, $\widetilde{c}$, n, $\widetilde{k}$ are given

$$
\begin{aligned}
n &= \left(\frac{(1-\alpha)(1-\tau)/\psi}{1-(1-(1-\delta)/\gamma)\widetilde{k}/\widetilde{y}}\right)^{\frac{1}{1+\kappa}} && (29)\\
\widetilde{y} &= \left(\frac{\widetilde{k}/\widetilde{y}}{\gamma}\right)^{\alpha/(1-\alpha)} n && (30)\\
\widetilde{c} &= \left(1-(1-(1-\delta)/\gamma)\widetilde{k}/\widetilde{y}\right)\widetilde{y} && (31)\\
\widetilde{k} &= (\widetilde{k}/\widetilde{y})\widetilde{y} && (32)
\end{aligned}
$$

where $\widetilde{k}/\widetilde{y} = \frac{\alpha(1-\tau)}{1/\beta-(1-\delta)/\gamma}$. These are the values along a deterministic balanced growth path with tax rate τ.

B Derivation of Equation (18)

The solution of the form (16) -(17) implies that, omitting constants,

$$
\begin{aligned}
\Delta(\ln K_t - \ln X_{t-1}) &= -(1-\phi_{kk}L)^{-1}\phi_{kk}(1-L)\varepsilon^x_{t-1} + (1-\phi_{kk}L)^{-1}\phi_{k\tau}(1-L)\hat{\tau}_{t-1}\\
\Delta \ln N_t &= \phi_{nk}\Delta(\ln K_t - \ln X_{t-1}) + \phi_{nx}(1-L)\varepsilon^x_t + \phi_{n\tau}(1-L)\hat{\tau}_t
\end{aligned}
$$

Combining yields

$$
\Delta \log N_t = (1-L)\left(\phi_{nx} - \frac{\phi_{nk}\phi_{kk}L}{1-\phi_{kk}L}\right)\varepsilon^x_t + \left(\phi_{n\tau} + \frac{\phi_{nk}\phi_{k\tau}L}{1-\phi_{kk}L}\right)\frac{1}{\tau}\varepsilon^\tau_t
$$

Furthermore, since $\ln(Y_t/N_t) = (1-\alpha)\ln X_t + \alpha(\ln K_t - \ln N_t)$, we have

$$\begin{aligned}
\Delta \ln(Y_t/N_t) &= (1-\alpha)\varepsilon_t^x + \alpha(\Delta \log K_t - \Delta \log N_t) \\
&= (1-\alpha(1-L))\,\varepsilon_t^x + \alpha(\Delta(\log K_t - \log X_{t-1}) - \Delta \log N_t) \\
&= \left(1-\alpha(1-L)\left(\frac{1}{1-\phi_{kk}L} + \phi_{nx} - \frac{\phi_{nk}\phi_{kk}L}{1-\phi_{kk}L}\right)\right)\varepsilon_t^x + \alpha\left(\frac{(1-\phi_{nk})\phi_{k\tau}L}{1-\phi_{kk}L} - \phi_{n\tau}\right)\frac{1}{\tau}\varepsilon_t^\tau
\end{aligned}$$

Finally, since $\ln(T_t) = \hat{\tau}_t + \ln(Y_t/N_t) + \ln N_t$, we have

$$\begin{aligned}
\Delta \ln(T_t) &= \frac{1}{\tau}\varepsilon_t^\tau + \Delta \ln(Y_t/N_t) + \Delta \ln N_t \\
&= \left(1 - \frac{\alpha(1-L)}{1-\phi_{kk}L} + (1-\alpha)(1-L)\left(\phi_{nx} - \frac{\phi_{nk}\phi_{kk}L}{1-\phi_{kk}L}\right)\right)\varepsilon_t^x \\
&\quad + \left(1 + \alpha\frac{\phi_{k\tau}L}{1-\phi_{kk}L} + (1-\alpha)\left(\phi_{n\tau} + \frac{\phi_{nk}\phi_{k\tau}L}{1-\phi_{kk}L}\right)\right)\frac{1}{\tau}\varepsilon_t^\tau
\end{aligned}$$

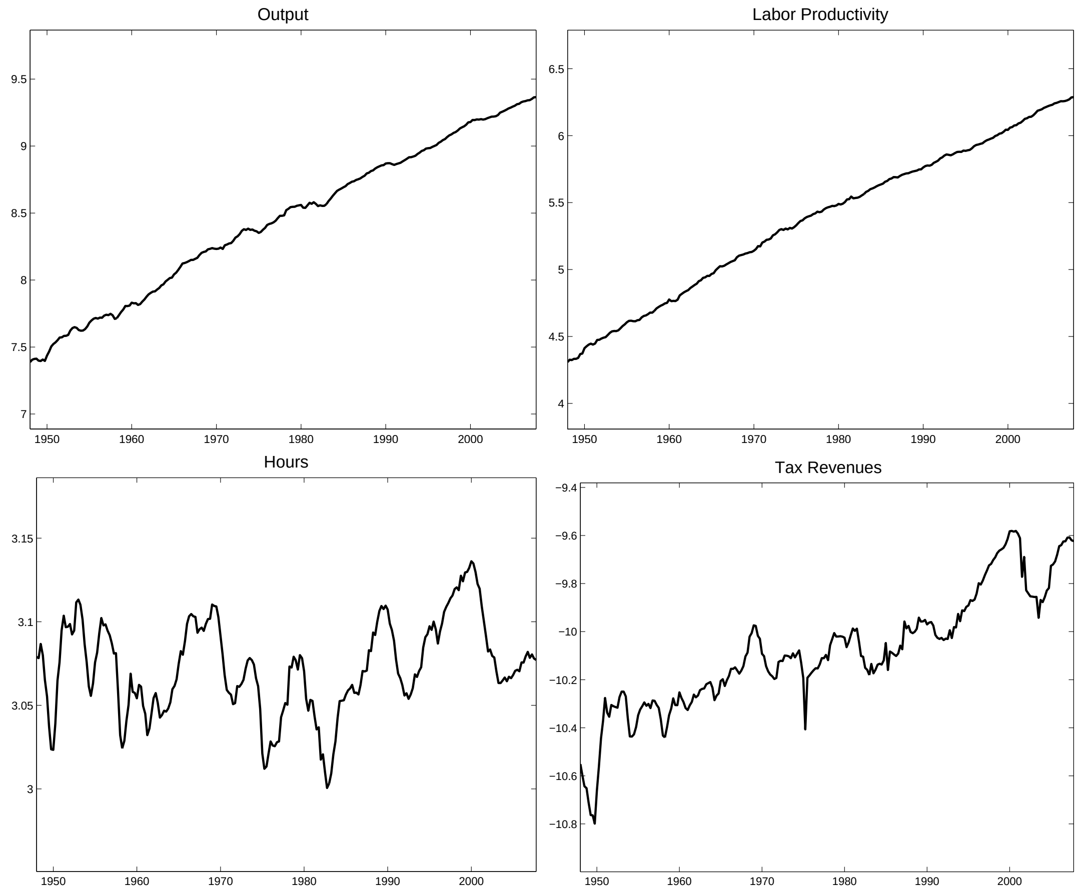


Figure 1: Time Series

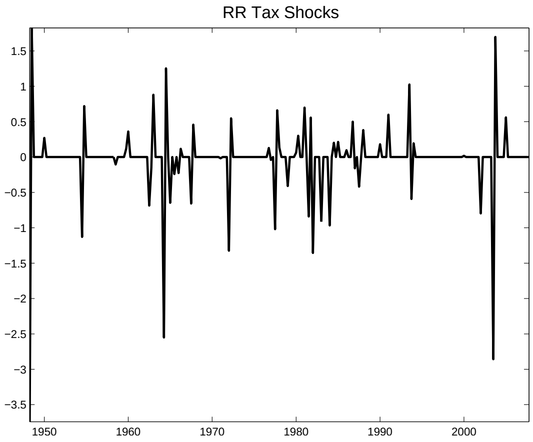
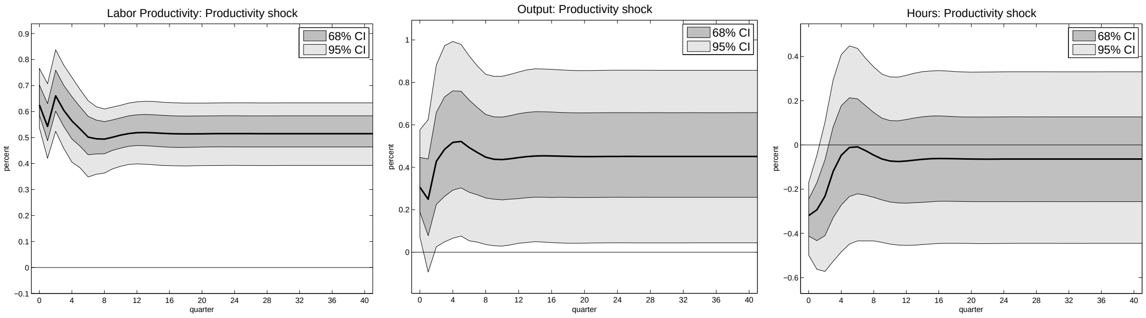


Figure 2: Romer and Romer (2008) Tax Shocks

(a) Hours in Differences



(b) Hours in Levels

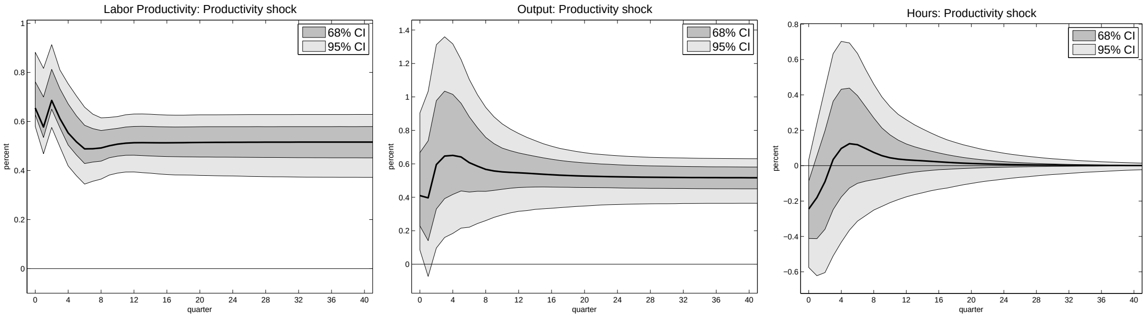


Figure 3: Productivity Shock in VAR with Labor Productivity and Hours

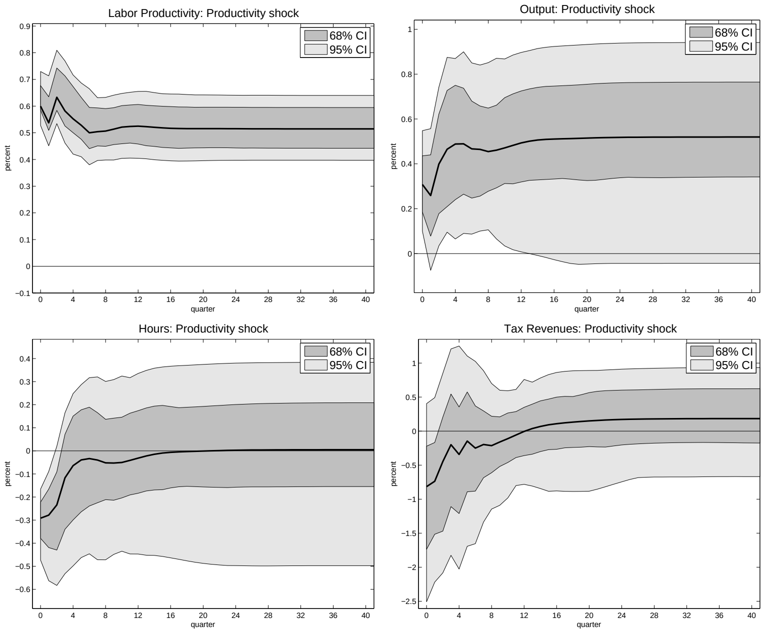


Figure 4: Productivity Shock in VECM with Labor Productivity, Hours and Tax Revenues

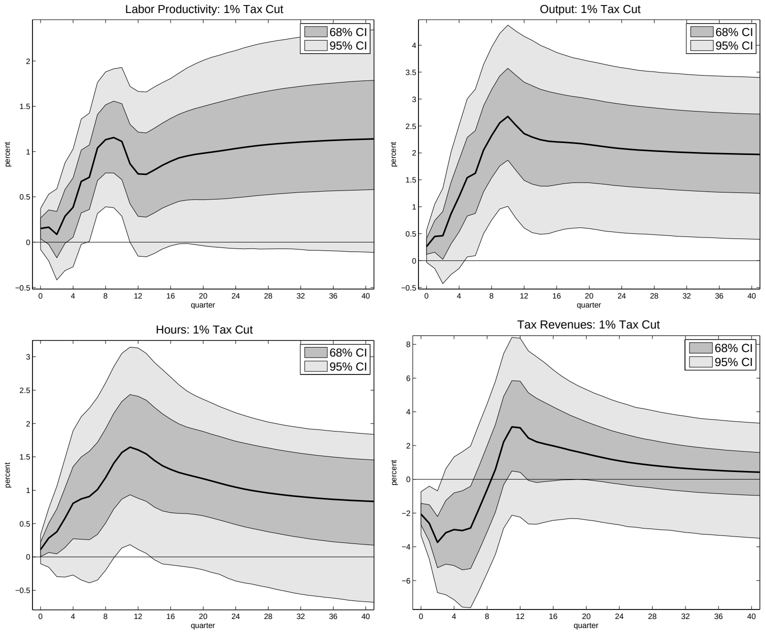


Figure 5: Tax Shock in the VECM with Romer and Romer's (2010) Tax Shocks.

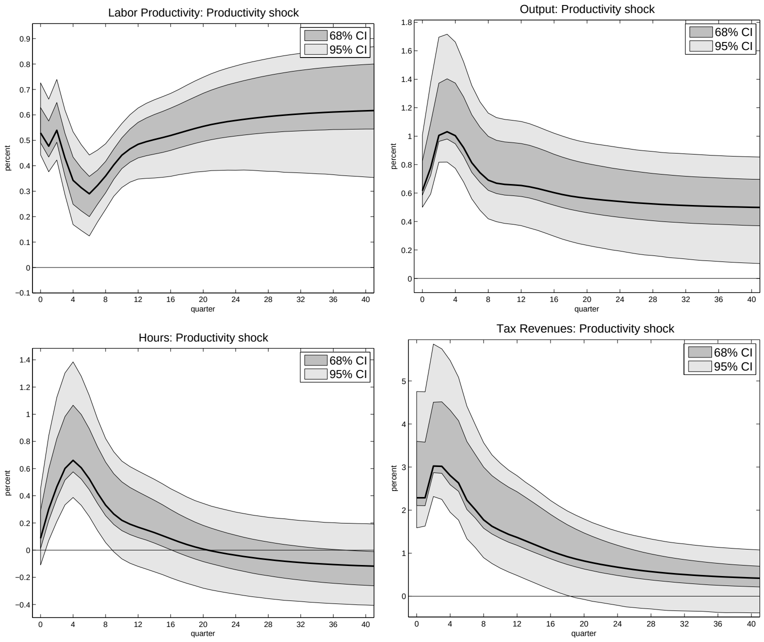


Figure 6: Productivity Shock in a VECM with Romer and Romer's (2010) Tax Shocks.

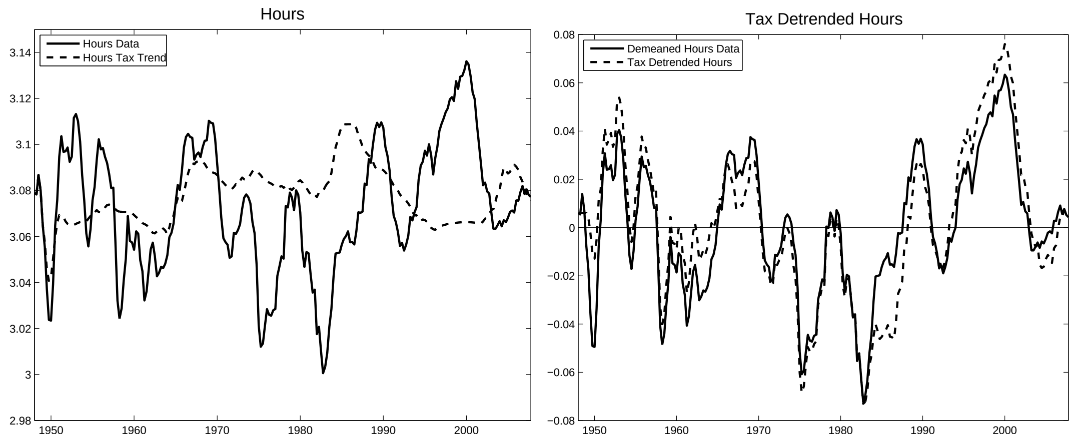


Figure 7: Hours and Permanent Tax Changes

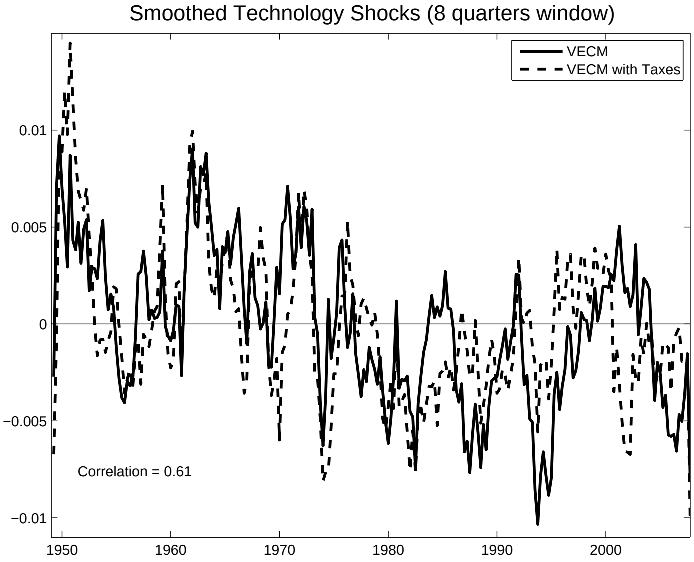
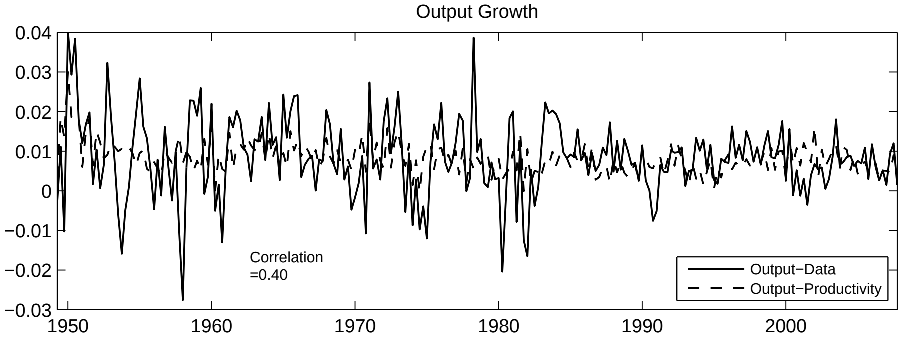


Figure 8: Estimated Technology Shocks

(a) VECM Without RR Tax Shocks



(b) VECM With RR Tax Shocks

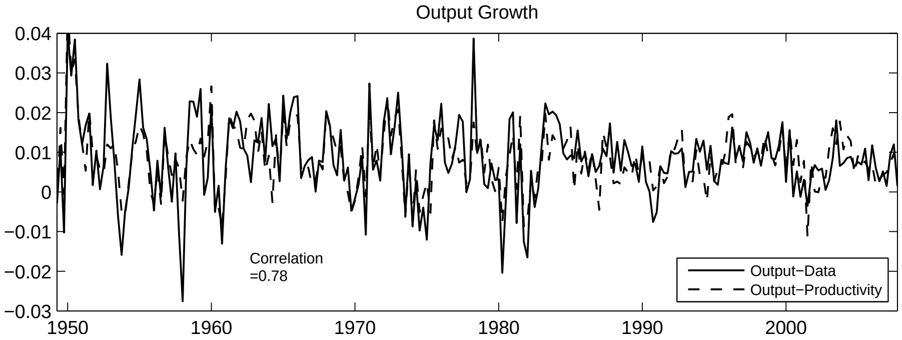


Figure 9: Output Growth Driven by Productivity Shocks

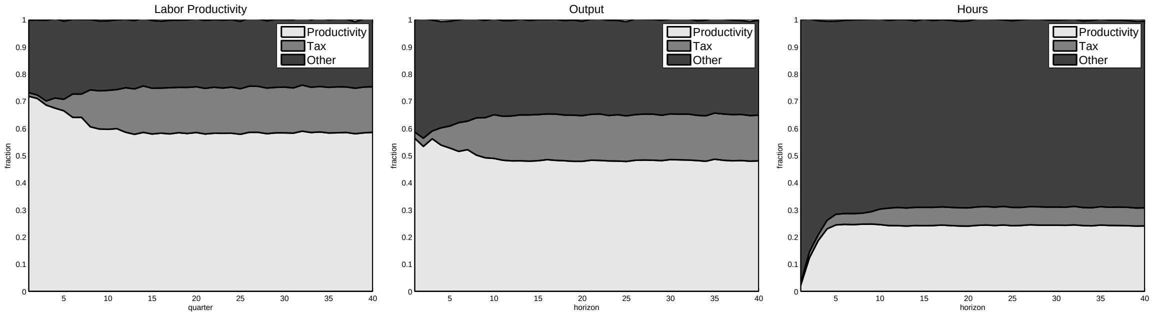


Figure 10: Forecast Error Variance Decomposition in VECM

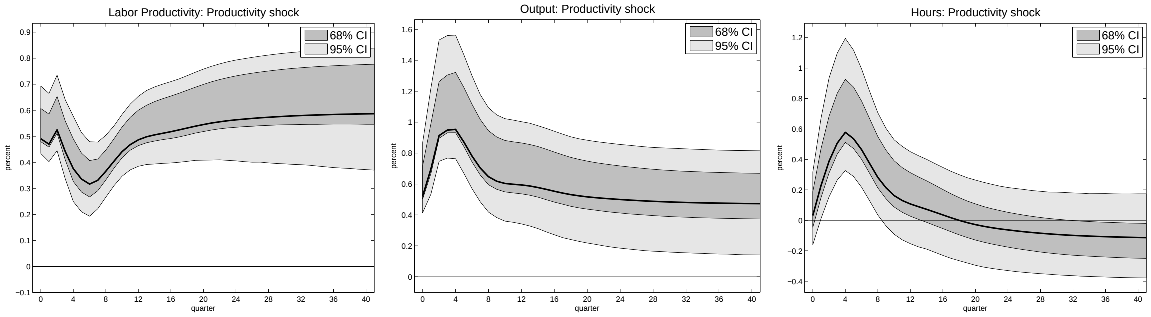
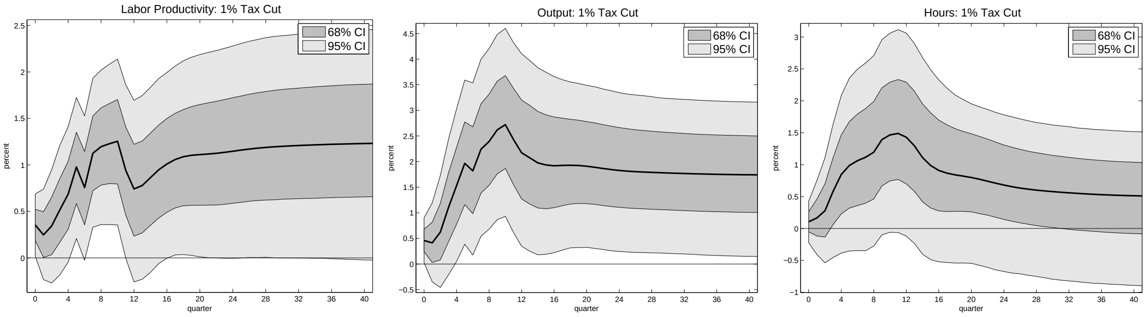


Figure 11: Productivity Shock in a VECM with Surprise and Anticipated Tax Shocks.

(a) Response to Surprise Tax Shock



(b) Response to Anticipated Tax Shock

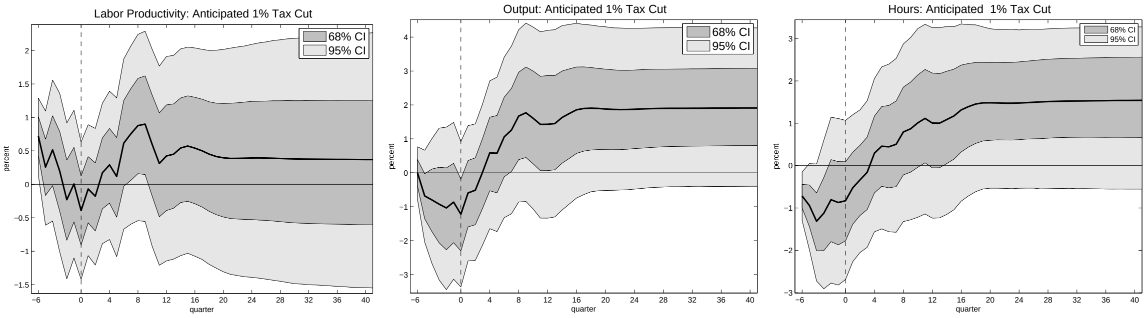


Figure 12: Tax Shock in the VECM with Surprise and Anticipated Tax Shocks.

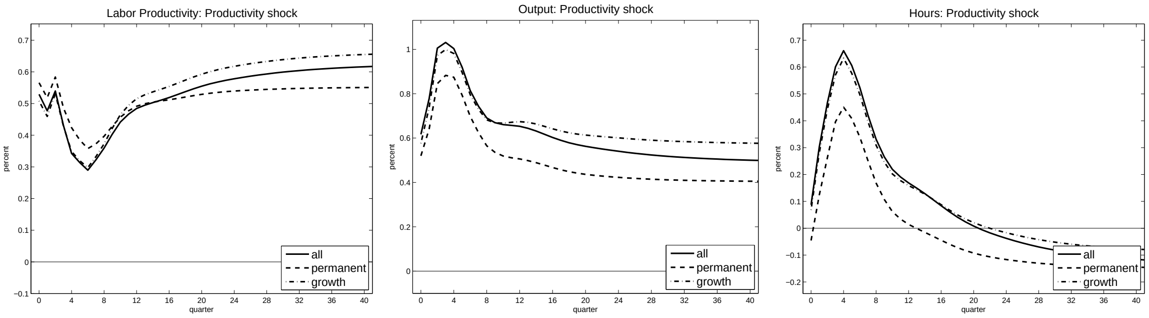


Figure 13: Productivity Shock: Including Alternative Tax Shock Measures.

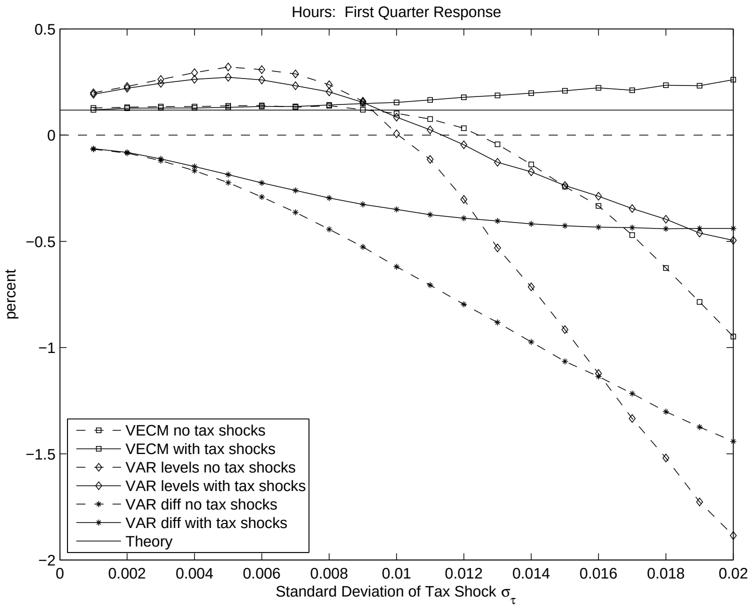


Figure 14: First Quarter Response of Hours to Productivity Shock in Simulations