The Dynamic Effects of Forward Guidance Shocks*

Brent Bundick[†] A. Lee Smith[‡]

First Version: January 2016
Current Version: December 2016

Abstract

We examine the macroeconomic effects of forward guidance shocks at the zero lower bound. Empirically, we identify forward guidance shocks using unexpected changes in futures contracts around monetary policy announcements. We then embed these policy shocks into a standard vector autoregression to trace out their macroeconomic implications. Forward guidance shocks that lower expected future policy rates lead to significant increases in economic activity and inflation. After examining forward guidance shocks in the data, we show that a standard model of nominal price rigidity can reproduce our empirical findings. To estimate our theoretical model, we generate a model-implied futures curve which closely links our model with the data. Our results suggest no disconnect between the empirical effects of forward guidance shocks and the predictions from a simple theoretical model.

JEL Classification: E32, E52

Keywords: Forward Guidance, Federal Funds Futures, Zero Lower Bound, Impulse Response Matching

*We thank Susanto Basu, Troy Davig, Christopher Otrok, and Stephen Terry for helpful discussions. We also thank our formal discussants, James D. Hamilton, Silvia Miranda-Agrippino, and Benjamin Born, for useful comments. We have benefited from comments made by participants at various seminars and conferences. Thealexa Becker and Trenton Herriford provided excellent research assistance and we thank CADRE for computational support. The views expressed herein are solely those of the authors and do not necessarily reflect the views of the Federal Reserve Bank of Kansas City or the Federal Reserve System. Available: http://dx.doi.org/10.18651/RWP2016-02

[†]Federal Reserve Bank of Kansas City. Email: brent.bundick@kc.frb.org

[‡]Federal Reserve Bank of Kansas City. Email: andrew.smith@kc.frb.org

1 Introduction

In December 2008, the Federal Open Market Committee (FOMC) lowered the federal funds rate to its effective lower bound. With economic conditions continuing to deteriorate and its conventional policy tool unavailable, the Federal Reserve announced its intention to keep future policy rates exceptionally low "for some time." Such communication about the future path of policy, known as forward guidance, became a fixture of U.S. monetary policy in subsequent years.

However, recent theoretical and empirical works are divided on the macroeconomic effects of forward guidance. In standard models with nominal price rigidities, Eggertsson and Woodford (2003) show that lowering the expected path of policy rates can be highly effective in increasing economic activity and inflation. However, Del Negro, Giannoni and Patterson (2012) and Kiley (2016) argue that these theoretical models overpredict the expansionary effects of forward guidance. In contrast, empirical work by Campbell et al. (2012) and Nakamura and Steinsson (2015) argues that communicating lower expected rates may signal bad news about the state of the economy. Through this macroeconomic news effect, these papers suggest that lower expected policy rates may cause contractions in expected economic activity and employment.

We examine this apparent disconnect between the empirical evidence and theoretical predictions of macroeconomic models. First, we study the empirical effects of forward guidance shocks at the zero lower bound. We identify forward guidance shocks in the data using the unexpected changes in high-frequency futures contracts following FOMC announcements. To trace out the dynamic effects of these policy changes on macroeconomic aggregates, we embed our identified forward guidance shocks into a standard vector autoregression (VAR). We find that forward guidance shocks that lower expected future policy rates result in a persistent economic expansion. At their peak response, output and prices increase by over 10 basis points following a one standard deviation forward guidance shock. Our findings are robust to alternative ordering schemes in the VAR, different measures of economic activity and prices, and alternative measures of expected future interest rates. Similar to conventional policy shocks, we find that forward guidance shocks can produce significant increases in economic activity but only explain a modest fraction of overall business-cycle fluctuations.

After identifying forward guidance shocks in the data, we examine their effects in a standard model of nominal price rigidity. Using a nonlinear solution method, we estimate a standard New-Keynesian model with a zero lower bound constraint. We model a forward guidance shock as an exogenous innovation to the central bank's desired policy rate at the zero lower bound. When desired rates are less than zero, an exogenous shock to the desired rate acts like an exogenous extension of the zero lower bound episode. This exogenous extension of the zero lower bound lowers future expected policy rates, which we link with our identified forward guidance shock in the data. To closely align with the futures contracts from our empirical results, we generate a model-implied futures curve using the household's stochastic discount factor. Using impulse response matching, we estimate our nonlinear model such that a forward guidance shock in the model generates the same movements in futures rates that we observe in the data.

Our theoretical model can reproduce the macroeconomic effects of forward guidance shocks we find in the data. In the model, an exogenous decline in expected future policy rates generates movements in economic activity and prices similar in shape and magnitude to our empirical responses. The key features of our model are a reasonable degree of nominal price rigidity, habits in household consumption, investment adjustment costs, variable capital utilization, and a persistent forward guidance shock process. Our results suggest that dynamic equilibrium models, with a mix of nominal and real rigidities, remain useful in examining the effects of monetary policy shocks both at and away from the zero lower bound.

Our findings suggest no disconnect between the empirical effects of forward guidance shocks and the predictions from a standard theoretical model. Thus, we argue that the "Forward Guidance Puzzle" posited by Del Negro, Giannoni and Patterson (2012) may be overstated. Our conclusion relies on estimating the appropriate-sized forward guidance shock using the model-implied futures curve. In both our empirical evidence and theoretical model, a typical expansionary forward guidance shock moves 12-month ahead futures rates by about three basis points. This shock extends the zero lower bound duration by one month in our model. Del Negro, Giannoni and Patterson (2012), however, simulate a much longer one-year exogenous extension of the zero lower bound period. In our high-frequency identification of policy shocks, we do not observe forward guidance shocks of that size in the data. Thus, we simulate a much smaller forward guidance shock in the model that is consistent with the typical movements in futures rates around policy meetings.

2 Forward Guidance Shocks in the Data

We use a two-step procedure to examine the macroeconomic effects of forward guidance shocks in the data. First, we identify the exogenous forward guidance shocks associated with each FOMC meeting. Using high-frequency measures of future policy rates, we examine how the implied path of policy rates changes after each policy announcement. Then, we embed these policy shocks into a standard block-recursive monetary VAR to trace out the dynamic effects on macroeconomic aggregates.

In our baseline results, we focus on estimating the effects of forward guidance shocks at the zero lower bound. Thus, we restrict our initial analysis to the December 2008 - December 2015 sample period. We make this sample selection for three reasons. First, the zero lower bound period allows us to easily identify changes in the path of future rates while holding the current level of policy rates constant. Away from the zero lower bound, identifying forward guidance shocks requires us to isolate changes in the path of rates from fluctuations in the current policy rate. While we undertake such a decomposition in Section 5, we opt for a simpler identification scheme in our baseline results. Second, this easier identification scheme allow us to easily map our empirical evidence in a standard theoretical model. Finally, focusing on the most recent period avoids contaminating our results with any structural change that may occur as the economy enters and exits the zero lower bound.

2.1 High-Frequency Futures Data

In our baseline model, we use federal funds futures contracts to measure the expected path of future policy rates. These contracts payoff based on the average effective federal funds rate at a given month in the future. Around each regularly-scheduled FOMC meeting, we compute the daily change in policy rates implied by the 12-month ahead futures contract. Since futures prices should already reflect any expected policy change prior to the announcement, our measure of forward guidance shocks captures how one-year ahead policy expectations change with the surprise component of each monetary policy announcement. To generate a monthly series for the implied level of policy rates, we follow Romer and Romer (2004) and Barakchian and Crowe (2013) and assign a value of zero to months in which there is no FOMC meeting and cumulatively sum the resulting series. In the following section, we embed this policy measure in a monthly-frequency vector autoregression.

2.2 Baseline Empirical Model

We now embed our futures-implied policy shock series into a structural vector autoregression to trace out the macroeconomic effects of a forward guidance shock. We estimate our baseline empirical model at a monthly frequency using several indicators of real economic activity and a measure of aggregate prices. We include a monthly measure of GDP, a proxy for equipment investment, capacity utilization, the GDP deflator, and the policy rates implied by the 12-month ahead federal funds futures contract. We use the Macroeconomic Advisers monthly GDP and corresponding price deflator to measure aggregate real activity and prices. To proxy equipment investment at a monthly frequency, we use core capital goods shipments, which the Bureau of Economic Analysis uses to calculate the official quarterly investment data. Appendix A.1 contains more details on the data construction.

Following the previous literature on the effects of conventional policy shocks, we order our measure of forward guidance shocks last using a recursive identification scheme. This assumption implies that the macroeconomic conditions adjust slowly to changes in the expected policy rates. Given the monthly-frequency of our VAR, our baseline model assumes that a monetary policy announcement today does not affect the current month's economic indicators. At a monthly frequency, we believe this assumption seems plausible. However, this ordering assumption is not necessary for our main results. In Appendix A.2, we show that our results are unchanged if we order our policy shocks first or treat them as exogenous variables determined outside of the VAR.

We conduct statistical inference on the impulse responses using a Bayesian Monte Carlo procedure. Following Sims and Zha (1999), we use a non-informative conjugate prior such that the posterior distribution of the reduced form VAR parameters is centered at the ordinary least squares point estimates.[1] We use standard selection criteria to determine the number of lags to include in the vector autoregression.

2.3 Empirical Impulse Responses

We now return to our key empirical question: What are the macroeconomic effects of forward guidance shocks? Figure 1 plots the estimated impulse responses for an identified forward guidance shock with the 90% probability interval. A one standard deviation forward guidance shock lowers the implied one-year ahead federal funds rate by about three basis points.

[1] Our exact implementation follows Koop and Korobilis (2010).

In response to the shock, firms increase their output, raise prices, and invest in new capital. Per our ordering assumption, economic activity and prices remain unchanged at impact. In the following months, however, overall output rises sharply and remains elevated for the next three years. Investment and capacity utilization rise quickly after the shock and peak roughly one year after the policy shock. The fluctuations in investment are significantly larger than the movements in total output. Prices rise gradually over time, reaching their peak response about 24 months after the shock. At their peak response, output and prices both increase by over 10 basis points following the shock. Overall, our results suggest that an exogenous decline in expected policy rates at the zero lower bound broadly increases economic activity and prices.

2.4 Forecast Error Variance Decompositions

While forward guidance shocks can produce significant increases in economic activity, they only explain a modest fraction of overall business-cycle fluctuations. Table 3 contains the forecast error variance decompositions for our baseline empirical model across multiple horizons. At the two-year horizon, we find that forward guidance shocks explain less than 20 percent of the total unexpected fluctuations in output. For comparison, we also present the same variance decompositions for conventional monetary policy shocks using the previous empirical work of Romer and Romer (2004) and Christiano, Eichenbaum and Evans (2005). With respect to output, we find no statistically meaningful differences in the variance decompositions between our results and the findings of Romer and Romer (2004) and Christiano, Eichenbaum and Evans (2005).

However, we find that forward guidance shocks appear more important than conventional policy shocks in explaining short-run fluctuations in the price level. This differential conclusion is likely due to changes in the persistence of inflation over time. For example, Christiano, Eichenbaum and Evans (2005) estimate their model over the 1964-1995 sample period whereas we use data from 2008-2015. We find that prices respond fairly quickly after a forward guidance shock, peaking after about two years. In contrast, prices only gradually rise and peak after about four years in the model of Christiano, Eichenbaum and Evans (2005). These findings suggest substantially less inflation persistence after an identified monetary policy shock in our sample compared with previous studies.[2]

[2]Both Cogley, Primiceri and Sargent (2010) and Davig and Doh (2014) also argue that inflation persistence has declined since the 1970's

2.5 Robustness of Empirical Results

Our empirical findings are robust to alternative measures of monetary policy expectations, different empirical specifications, and other measures of economic activity and prices. During the zero lower bound period, our baseline empirical model assumes that one-year ahead futures rates fully capture the expected path of policy. Using this single expected interest rate to measure the path of policy helps us easily map our empirical framework into a theoretical model. However, our empirical findings are quantitatively unchanged if we instead use alternative measures of interest-rate expectations. In Section 6, we instead identify a forward shock using a principal component of a variety of interest-rate futures. In addition, Appendix A.3 shows that we find similar macroeconomic effects if we measure forward guidance shocks using two-year ahead Eurodollar rates. In Appendix A.4, we show our results are not sensitive to the number of lags included in our baseline VAR. Finally, Appendix A.5 shows that our results are robust to using industrial production and core producer prices as alternative measures of activity and prices.

Taken together, these results suggest that forward guidance shocks that lower expected future policy rates lead to a sustained and robust economic expansion. In the next section, we show that a standard model of nominal price rigidity can reproduce the macroeconomic effects of forward guidance shocks in the data. Our findings suggest no disconnect between the empirical effects of forward guidance shocks and the predictions from a standard theoretical model.

3 A Theoretical Model of Nominal Price Rigidity

This section outlines the dynamic stochastic general equilibrium model we use to analyze forward guidance shocks. The model shares features with the models of Ireland (2003), Ireland (2011), and Christiano, Eichenbaum and Evans (2005). Our model features optimizing households and firms and a central bank that systematically adjusts the nominal interest rate to offset shocks to the economy. We allow for sticky prices using the staggered price-adjustment specification of Calvo (1983). The model considers shocks to household preferences and the central bank's desired policy rate. To link the theoretical model with our previous empirical results, we use the household's stochastic discount factor to generate a model-implied futures curve. Following Christiano, Eichenbaum and Evans (2005), we assume that household consumption and firm pricing decisions are made prior to the realization of shocks in the economy. This timing assumption ensures that the impact response of the macroeconomic aggregates in the model following a forward guidance shock are consistent with the recursive identification scheme from our empirical evidence. Appendix B shows all of the model's equilibrium conditions in greater detail.

3.1 Households

In the model, the representative household maximizes lifetime expected utility over streams of consumption C_t and leisure $1 - N_t$. Households derive utility from consumption relative to a habit level H_t. The household receives labor income W_t for each unit of labor N_t supplied in the representative intermediate goods-producing firm. The household also owns the intermediate goods firm, which pays lump-sum dividends D_t. Also, the household has access to zero net-supply nominal bonds B_t and real bonds B_t^R. Nominal bonds pay one nominal dollar and are purchased with a discounted price $1/R_t$, where R_t denotes the one-period gross nominal interest rate. Real bonds return one unit of consumption and have a purchase price $1/R_t^R$, where R_t^R denotes the one-period gross real interest rate. The household divides its income from labor and its financial assets between consumption C_t and the amount of the bonds B_{t+1} and B_{t+1}^R to carry into next period.

The representative household maximizes lifetime utility by choosing $C_{t+s}, N_{t+s}, B_{t+s+1}$, and B_{t+s+1}^R, for all $s = 0, 1, 2, \ldots$ by solving the following problem:

$$\max \mathrm{E}_{t-1} \sum_{s=0}^{\infty} a_{t+s} \beta^s \left(\log \left(C_{t+s} - bH_{t+s} \right) - \xi \frac{N_{t+s}^{1+\eta}}{1+\eta} \right)$$

subject to the intertemporal household budget constraint each period,

$$C_t + \frac{1}{R_t} \frac{B_{t+1}}{P_t} + \frac{1}{R_t^R} B_{t+1}^R \leq \frac{W_t}{P_t} N_t + \frac{B_t}{P_t} + \frac{D_t}{P_t} + B_t^R.$$

λ_t denotes the Lagrange multiplier on the household budget constraint. In equilibrium, consumption habits are formed external to the household and are linked to last period's aggregate consumption $H_t = C_{t-1}$.

The discount factor of the household β is subject to shocks via the stochastic process a_t. We interpret these fluctuations as demand shocks since an increase in a_t induces households to consume more and work less for no technological reason. We use these shocks to simulate a large decline in household demand which generates a zero lower bound episode. The stochastic process for these fluctuations is as follows:

$$a_t = (1 - \rho_a) a + \rho_a a_{t-1} + \sigma^a \varepsilon_t^a \tag{1}$$

where ε_t^a is an independent and standard normal random variable.

3.2 Final Goods Producers

The representative final goods producer uses Y_{it} units of each intermediate good produced by the intermediate goods-producing firm $i \in [0, 1]$. The intermediate output is transformed into final output Y_t using the following constant returns to scale technology:

$$\left[\int_0^1 Y_{it}^{\frac{\theta-1}{\theta}} di\right]^{\frac{\theta}{\theta-1}} \geq Y_t,$$

where θ is the elasticity of substitution across intermediate goods. Each intermediate good Y_{it} sells at nominal price P_{it} and the final good sells at nominal price P_t. The finished goods producer chooses Y_t and Y_{it} for all $i \in [0, 1]$ to maximize the following expression of firm profits:

$$P_t Y_t - \int_0^1 P_{it} Y_{it} di$$

subject to the constant returns to scale production function. Finished goods-producer optimization results in the following first-order condition:

$$Y_{it} = \left[\frac{P_{it}}{P_t}\right]^{-\theta} Y_t.$$

The market for final goods is perfectly competitive, and thus the final goods-producing firm earns zero profits in equilibrium. Using the zero-profit condition, the first-order condition for profit maximization, and the firm objective function, the aggregate price index P_t can be written as follows:

$$P_t = \left[\int_0^1 P_{it}^{1-\theta} di\right]^{\frac{1}{1-\theta}}.$$

3.3 Intermediate Goods Producers

Each intermediate goods-producing firm i rents labor N_{it} from the representative household to produce intermediate good Y_{it} in a monopolistically competitive market. Each period, producers can reoptimize their nominal price P_{it} with a constant probability $1 - \omega$. Firms that cannot chose a new optimal price index their current price to a weighted combination of past and steady state inflation rates. The intermediate-goods firms own their capital stocks K_{it} and face convex costs κ of changing its level of investment I_{it}. Firms also choose the rate of utilization of their installed physical capital U_{it} which affects its depreciation rate. The intermediate goods firms all have access to the same constant returns-to-scale production function. We introduce a production subsidy $\Psi = \theta/(\theta - 1)$ to ensure that the steady state of the model is efficient. Firms rebate any profits to the household in lump-sum each period.

We determine the optimal decisions of the intermediate goods-producing firm in two steps. First, firms determine the minimal cost method to meet the current level of demand for their product. Thus, each firm solves the following cost minimization problem:

$$\min \mathrm{E}_{t-1} \sum_{s=0}^{\infty} \left(\beta^s \frac{\lambda_{t+s}}{\lambda_t} \right) \left(\frac{W_{t+s}}{P_{t+s}} N_{i,t+s} + I_{i,t+s} \right)$$

subject to the production function,

$$Y_{it} \leq \left(K_{it} U_{it} \right)^{\alpha} \left(N_{it} \right)^{1-\alpha}$$

and its capital accumulation equation,

$$K_{it+1} = \left(1 - \delta\left(U_{it} \right) \right) K_{it} + \left(1 - \frac{\kappa}{2} \left(\frac{I_{it}}{I_{it-1}} - 1 \right)^2 \right) I_{it}.$$

We assume depreciation depends on utilization via the following functional form:

$$\delta\left(U_{it} \right) = \delta + \delta_1 \left(U_{it} - U \right) + \left(\frac{\delta_2}{2} \right) \left(U_{it} - U \right)^2.$$

Ξ_t denotes the marginal cost of producing one additional unit of intermediate good i and q_t is the price of a marginal unit of installed capital.

After solving its cost minimization problem, firms that can reoptimize choose their optimal price to maximize their lifetime discounted real profits. Their profit maximization problem is as follows:

$$\max \mathrm{E}_{t-1} \sum_{s=0}^{\infty} \omega^s \beta^s \frac{\lambda_{t+s}}{\lambda_t} \left(\Psi \, \Pi^{s(1-\chi)} \Pi_{t-1,t-1+s}^{\chi} \frac{P_{it}}{P_{t+s}} Y_{it+s} - \Xi_{t+s} Y_{it+s} \right)$$

subject to the following demand curve,

$$Y_{it+s} = \left[\Pi^{s(1-\chi)} \Pi_{t-1,t-1+s}^{\chi} \frac{P_{i,t}}{P_{t+s}} \right]^{-\theta} Y_{t+s}.$$

The inflation rate between periods t and $t+s$ is defined as follows:

$$\Pi_{t,t+s} = \begin{cases} 1 & s = 0 \\ \frac{P_{t+1}}{P_t} \times \frac{P_{t+2}}{P_{t+1}} \times \cdots \times \frac{P_{t+s}}{P_{t+s-1}} & s = 1, 2, \ldots \end{cases}$$

The parameter χ controls the amount of indexation to lagged inflation.

3.4 Equilibrium

In the symmetric equilibrium, all intermediate goods firms face the same marginal costs and hence choose to employ the same amount of labor, capital, and utilization rate. All firms that can change their nominal price choose the same optimal price P_t^*. We denote the gross one-period inflation rate as $\Pi_t = P_t/P_{t-1}$. Under the assumption of Calvo (1983) pricing frictions, the aggregate price index P_t evolves as follows:

$$P_t^{1-\theta} = \theta\Big(\Pi^{1-\chi}\,\Pi_{t-1}^{\chi}\Big)^{1-\theta}\big(P_{t-1}\big)^{1-\theta} + \Big(1-\theta\Big)\big(P_t^*\big)^{1-\theta}$$

3.5 Monetary Policy

We assume a cashless economy where the monetary authority sets the one-period net nominal interest rate $r_t = \log(R_t)$. Due to the zero lower bound on nominal interest rates, the central bank cannot lower its nominal policy rate below zero. In the spirit of Reifschneider and Williams (2000), we assume the monetary authority sets its policy rate according to the following history-dependent policy rule subject to the zero lower bound:

$$r_t^d = \phi_r r_{t-1}^d + \Big(1-\phi_r\Big)\Big(r + \phi_\pi\big(\mathrm{E}_{t-1}\pi_t - \pi\big) + \phi_y \mathrm{E}_{t-1}y_t\Big) + \nu_t \tag{2}$$

$$\nu_t = \rho_\nu \nu_{t-1} + \sigma^\nu \varepsilon_t^\nu \tag{3}$$

$$r_t = \max\Big(0, r_t^d\Big) \tag{4}$$

where r_t^d is the desired policy rate of the monetary authority and r_t is the actual policy rate subject to the zero lower bound. π_t denotes the log of the one-period gross inflation rate Π_t and y_t is the gap between current and steady state output. Finally, ν_t is an autocorrelated monetary policy shock. Away from the zero lower bound, this policy rule acts like a Taylor (1993)-type policy rule with interest-rate smoothing. An exogenous ε_t^ν shock away from the zero lower bound acts like a conventional monetary policy shock.

When the economy encounters the zero lower bound, however, this history-dependent rule lowers the future path of policy to help offset the previous higher-than-desired nominal rates caused by the nominal constraint. Households fully internalize this future conduct of policy. When desired rates are less than zero, an exogenous shock to the desired rate ε_t^ν acts like an exogenous extension of the zero lower bound episode. This exogenous extension of the zero lower bound lowers future expected policy rates, which we link with our identified forward guidance shock in the data. Thus, our specification of monetary policy allows us to analyze both conventional policy shocks away from the zero lower bound and forward guidance shocks at the zero lower bound.

Our forward guidance shock specification differs from the work of Del Negro, Giannoni and Patterson (2012) and Keen, Richter and Throckmorton (2015), which use a combination of current and anticipated monetary policy shocks to model forward guidance shocks. However, we prefer our specification for two reasons. First, our specification is parsimonious and only adds a single state variable (the central bank's desired rate) to the model. In contrast, anticipated news shocks add an additional state variable for each horizon of central bank forward guidance. Second, we find simulating forward guidance using news shocks somewhat cumbersome. As Keen, Richter and Throckmorton (2015) discuss, an anticipated policy shock which lowers future expected policy rates causes output and inflation to rise today. Through the endogenous component in the central bank's policy rule, higher output and inflation implies higher policy rates today. Thus, to keep rates unchanged today, the economic modeler must simulate an additional *expansionary* contemporaneous policy shock to keep rates unchanged today. By contrast, our single forward guidance shock acts like an exogenous extension of the zero lower bound episode that leaves current policy rates unchanged. We believe this analysis closely aligns with the type of experiments envisioned by policymakers.

3.6 Generating Model-Implied Futures Contracts

A key issue in determining the effects of forward guidance is choosing the appropriate values for the exogenous shock process. We want to ensure our simulated forward guidance shock in the model is consistent with the forward guidance shock we identify in the data. Therefore, we generate a model counterpart to the federal funds futures contracts in the data. We denote the price of a n-month ahead futures contract at time t by f_t^n. The payoff on this contract is one minus the average effective federal funds rate over the contract expiration month. For the 1-month ahead contract in our model, this payoff concept equals $1 - 12r_{t+1}$, where r_{t+1} is the monthly policy rate of the central bank next period. Using the household stochastic discount factor, we calculate the price of the one-month ahead zero net-supply futures contract by including the following equilibrium condition:

$$1 = \mathrm{E}_t \left\{ \left(\beta \frac{\lambda_{t+1}}{\lambda_t} \right) \frac{R_t}{\Pi_{t+1}} \frac{1 - 12r_{t+1}}{f_t^1} \right\}. \qquad (5)$$

The structure of the futures contracts implies that an n-month contract at time t becomes an $n-1$ contract at time $t+1$. Thus, we price out the entire futures curve using the additional equilibrium condition:

$$1 = \mathrm{E}_t \left\{ \left(\beta \frac{\lambda_{t+1}}{\lambda_t} \right) \frac{R_t}{\Pi_{t+1}} \frac{f_{t+1}^{n-1}}{f_t^n} \right\}, \tag{6}$$

for each monthly contract from $n = 2, \ldots, 12$.

These model counterparts allow us to determine the appropriate-sized forward guidance shock to simulate in the model. For a given horizon, we can determine the futures-implied interest rate by computing one minus the contract price. Note that we have included an additional term R_t/Π_{t+1} in each equilibrium condition. In reality, investors in federal funds futures contracts must post collateral when entering futures positions. Since the collateral also earns a return, there is no opportunity cost of funds associated with futures positions. For tractability, our equilibrium conditions assume that the household enters these contracts using one-period nominal bonds each period. To be consistent with the timing assumptions in our structural VAR, we assume that futures prices can change in the same period as the forward guidance shock but output and prices are fixed at impact.[3]

3.7 Solution Method

We solve our model using the OccBin toolkit developed by Guerrieri and Iacoviello (2015). This solution method allows us to model the occasionally-binding zero lower bound and solve for the model-implied futures prices. The algorithm takes only a few seconds to solve the model, which permits us to estimate several key model parameters using impulse response matching. The solution method constructs a piecewise linear approximation to the original nonlinear model. We have also solved a fully nonlinear, but simplified, version of our model with the policy function iteration method of Coleman (1990) and Davig (2004). We find that the Guerrieri and Iacoviello (2015) toolkit provides a good approximation dynamics of the full nonlinear economy after a forward guidance shock.

[3]We could provide further microfoundations for this timing assumption using a two-agent household structure with workers and financial market participants. Workers would supply labor to the intermediate-goods producing firm and financial market participants would specialize in trading futures contracts. Under the assumption of consumption sharing within the household, this alternative model would produce identical results.

3.8 Estimation Strategy

Our estimation strategy examines movements in futures rates both in the data and model. The estimation procedure picks the size and persistence of the forward guidance shock such that the model generates the same movement in 12-month ahead futures rates we observe in the data. Without disciplining movements in the model-implied expected future interest rates, it is unclear what size forward guidance shock to simulate in the model. Our strategy is broadly consistent with previous monetary policy shock literature, which chooses the conventional monetary policy shock such that the movements in the model-implied policy indicator are consistent with the identified responses of the vector autoregression. However, since we focus on forward guidance shocks during the zero lower bound period, we discipline the model using expectations of future policy rates.

Following much of the previous literature, we partition the model parameters into two groups. The first group is composed of β, Π, η, ξ, θ, ϕ_π, ϕ_y, ρ_a, σ^a. We calibrate these parameters using steady-state relationships or results from previous studies. Since the model shares features with the models of Ireland (2003) and Ireland (2011), we calibrate some of our parameters to match his values or estimates. To match our empirical evidence, we calibrate the model to monthly frequency. We calibrate ξ to normalize output Y to equal one at the deterministic steady state. We choose standard values for the monetary policy reactions to inflation and output ($\phi_\pi = 1.5$, $\phi_y = 0.1$). Our monthly calibrations of β and Π imply a steady state annualized real interest rate of two percent and a two percent inflation target.

We estimate the second set of model parameters which consists of the household habit parameter b, the probability that a firm can not reoptimize its price ω, the degree of lagged inflation indexation χ, the degree of smoothing in the monetary policy rule ϕ_r, the amount of investment adjustment costs κ, the elasticity of the return on capital with respect to capacity utilization $\sigma_\delta = \delta_2/\delta_1$, and the forward guidance shock parameters ρ_ν and σ^ν. In addition, we also estimate the size of the initial negative demand shock ε_0^a which takes the economy to the zero lower bound prior to the forward guidance shock. We collect these parameters into a vector $\gamma = (b, \omega, \chi, \phi_r, \kappa, \sigma_\delta, \rho_\nu, \sigma_\nu, \varepsilon_0^a)$.

Using a Bayesian impulse response matching estimator, we estimate these key model parameters by finding the values which maximize their posterior distribution. Let $\hat{\psi}$ denote the impulse response functions for the 5 variables in our empirical VAR stacked into a single vector with $(5 \times 48 = 240)$ rows and let the diagonal matrix V^{-1} denote a measure of the precision of the estimated impulse responses.[4] Then, let $\psi(\gamma)$ denote the theoretical model's corresponding counterpart to $\hat{\psi}$. Following Christiano, Trabandt and Walentin (2010), we can write the approximate likelihood function as follows:[5]

$$L(\hat{\psi} \mid \gamma, V) = (2\pi)^{-\frac{N}{2}} \mid V \mid^{-\frac{1}{2}} \exp\left[-0.5(\hat{\psi} - \psi(\gamma))' V^{-1} (\hat{\psi} - \psi(\gamma))\right].$$

With the likelihood function in hand, let $p(\gamma)$ denote the joint prior density over γ. According to Bayes' rule,

$$f(\gamma \mid \hat{\psi}, V) \propto L(\hat{\psi} \mid \gamma, V) p(\gamma). \tag{7}$$

where $f(\gamma \mid \hat{\psi}, V)$ is the posterior density over γ. Our estimator solves the following problem:

$$\max_{\gamma} f(\gamma \mid \hat{\psi}, V). \tag{8}$$

3.9 Priors Over Parameters

For our priors, we use a Beta distribution for parameters that lie between 0 and 1 and a Gamma distribution for parameters which are positive but unbounded. For the household habit parameter b, degree of indexation χ, and the persistence of the forward guidance shock ρ_ν, we center the prior mode at 0.5 with a standard deviation of 0.25. For the Calvo parameter ω, we center our prior mode at 0.93 which is consistent Nakamura and Steinsson (2008)'s evidence that prices remain fixed for about one year on average. Our prior standard deviation over ω is fairly small at 0.02, which communicates the high weight we place on this micro-level evidence. We center our prior mode over ϕ_r at 0.75 which is consistent with a large literature arguing that historical Federal Reserve policy features a high degree of inertia. As we discuss in Section 3.5, however, the interpretation of this parameter changes when the economy is at the zero lower bound. Therefore, while we center our prior at previous estimates of interest-rate smoothing, we put a low degree of precision on this prior and set the prior standard deviation to 0.25.

[4] In particular, each element along the diagonal of V^{-1} contains one over the absolute value of the difference between the 95th and 5th percentile of the confidence interval. Following Christiano, Eichenbaum and Evans (2005), this construction of V^{-1} implies that the estimator $\hat{\gamma}$ attempts to place the model impulse responses inside the confidence intervals of the impulse responses from the data.

[5] Christiano, Eichenbaum and Trabandt (2016) provide three reasons why this is only an approximate likelihood: (i) Standard asymptotic theory implies that under the assumption that the DSGE model is the correct data generating process with the true parameters γ_0, $\hat{\psi}$ converges only asymptotically to $N(\psi(\gamma_0, V)$ as the sample size grows arbitrarily large, (ii) our proxy for V is guaranteed to be correct only as the sample size grows arbitrarily large, and (iii) $\psi(\gamma)$ is approximated with a piece-wise linear DSGE model.

For the investment adjustment cost parameter κ and elasticity of capital utilization σ_δ, we center our prior at the quarterly estimates of Christiano, Eichenbaum and Evans (2005). However, since our model is calibrated to monthly frequency, we set a very large standard deviation for these priors to reflect our uncertainty over the exact time-aggregation function. Our prior for the size of the forward guidance shock σ_ν is similarly uninformative and we restrict initial aggregate demand shock ε_0^a to be positive.[6]

4 Estimated Responses to a Forward Guidance Shock

We now analyze the macroeconomic effects of a forward guidance shock in our estimated model. To compute the impulse response, we generate two time paths for the economy. In the first time path, we simulate a large negative demand shock which causes the zero lower bound to bind for nine months. In the second time path, we simulate the same large negative first moment demand shock but also simulate a negative shock to the desired policy rate in Equation 2. This forward guidance shock implies that the 12-month ahead model-implied futures rates declines by about three basis points, which is consistent with our empirical findings in Section 2. We assume that the economy is hit by no further shocks and compute the percent difference between the two time paths as the impulse response to a forward guidance shock at the zero lower bound. Since the economy is at the zero lower bound, this exogenous shock to the desired rates acts like an exogenous extension of the zero lower bound period. In the estimated model, this forward guidance shock exogenously extends the zero lower bound duration by one month.

The model can reproduce the effects of a forward guidance shock in the data. Figure 1 plots both the empirical and model-implied impulse responses to a forward guidance shock. Output, investment, and capacity utilization in the model all rise in hump-shaped patterns similar to their empirical counterparts. The model also replicates the gradual increase in prices we observe in the data. While the peak response of output occurs earlier than in the data, the timing of the peak in output is not estimated very precisely. In fact, the model's response for output is always within the 90% probability interval of the data's impulse response function. Moreover, the model's responses for capacity utilization, prices, and futures rates almost always fall within their empirical probability intervals. These results suggest that the predictions from a standard model of monetary policy are generally in line with the empirical effects of a forward guidance shock.

[6] We multiply the initial demand shock by negative one to simulate a decline in aggregate demand, which takes the economy to the zero lower bound prior to the forward guidance shock.

The model struggles to generate sufficient movements in investment. However, recall that we proxy for investment at a monthly frequency using core capital goods shipments. While this measure is highly correlated with aggregate investment, it does not align exactly with the concept of investment in the national income accounts. For example, when aggregated to a quarterly frequency, core capital goods shipments are two to three times more volatile than the BEA's official investment series. Thus, when analyzing the models ability to match the data, we focus less on the model's ability to match the response of our investment proxy since it is a noisy indicator of underlying changes in the true capital stock.

Figure 2 shows the impulse responses for consumption, additional futures contracts, and real interest rates. Since households expect the zero lower bound to persist for ten months, 6-month ahead futures rates don't move immediately after the forward guidance shock. However, the 12-month ahead contracts fall by several basis points as expected nominal policy rates decline. The combination of the forward guidance shock, nominal price rigidity, and the zero lower bound produces a significantly hump-shaped response of real interest rates. At impact, current nominal policy rates are fixed at zero and expected inflation rises very slightly due to the nominal rigidity in price setting. Thus, real interest rates only fall modestly when the economy remains at the zero lower bound. However, real rates fall again once the economy exists the zero lower bound and the monetary authority can lower its current nominal policy rate. This time path for real interest rates causes a very gradual increase in consumption, where the peak response occurs about when the economy exits the zero lower bound.

4.1 Role of the Initial Demand Shock

While many features of our model are standard, simulating a forward guidance shock at the zero lower bound requires us to estimate the initial conditions in the economy prior to the forward guidance shock. In this section, we illustrate how our estimate of the initial aggregate demand shock affects our main results.

Disciplining the model using futures contracts helps the estimation procedure determine the appropriate zero lower bound episode to simulate in the model. In our baseline results, we find that a total zero lower bound episode of ten months allows the model to match the data. For comparison, we now simulate a larger initial shock to the economy such that the zero lower bound persists for significantly longer.[7] Figure 2 plots the responses under a two-year zero lower bound duration and our baseline 10-month scenario. If we simulate too large of an initial demand shock, the 12-month ahead futures rate fails to move at impact and displays a somewhat hump-shaped pattern. This time path is clearly inconsistent with the empirical evidence from Figure 1 where futures rates fall at impact and rise monotonically. Thus, appropriately choosing the initial demand shock ensures that the model can generate movements in futures rates similar to what we observe in the data.

4.2 Effects of Forward Guidance Shock Persistence

We find that the model greatly prefers a highly persistent forward guidance shock process to match the empirical impulse responses. Table 2 shows that our modal estimate of the forward shock persistence $\rho_\nu = 0.95$ with a very small standard error. In this section, we show why the estimation procedure favors this highly persistent shock process. We now solve an alternative model where we simulate a forward guidance shock without any persistence $\rho_\nu = 0$.[8] Figure 3 plots the model-implied impulse responses to both a persistent and iid forward guidance shock.

An autocorrelated forward guidance shock process helps the model generate a persistent decline in futures rates. In the data, futures rates remain lower for about 18 months following a typical forward guidance shock. Figure 1 shows that our baseline model easily replicates this feature of the data. Without a persistent shock process, however, Figure 3 shows that the model struggles to generate a persistent decline in futures rates. Since expected future policy rates don't fall enough, the alternative model then fails to generate sufficient movements in output and prices. Thus, a persistent shock process is crucial in matching both the path of the futures rates and the response of the other macroeconomic variables in response to a forward guidance shock.

4.3 Remaining Parameter Estimates

We now discuss the remaining estimated model parameters in Table 2. Our estimated degree of nominal rigidity ω implies that prices remain fixed for about 7 quarters on average. While

[7] In the estimation, we impose that the initial zero lower bound episode lasts for at least 6 months. This minimum constraint on the zero lower bound duration is consistent with the *ex ante* views of professional forecasters during 2009.

[8] In this alternative calibration, we also increase the size of the forward guidance shock to generate the same movement in futures rates at impact as our baseline model.

prices in our model are more persistent than in the micro-level estimates of Nakamura and Steinsson (2008), our results are consistent with the previous findings of Gali and Gertler (1999), Eichenbaum and Fisher (2007), and Christiano, Eichenbaum and Evans (2005).[9] The degree of lagged indexation in the Phillips curve is estimated to be $\chi = 0.3$, which is considerably smaller than Christiano, Eichenbaum and Evans (2005) who set $\chi = 1$ to match the responses to a conventional monetary policy shock. As we discuss in Section 2.4, this difference is likely due a decline in the persistence of inflation since the 1980s.

In addition to a moderate degree of nominal rigidity, the model requires some real-rigidities to match the data. Our estimate of consumption habits $b = 0.78$ is in line with estimates from Ferson and Constantinides (1991). As in Christiano, Eichenbaum and Evans (2005), our estimate of the capacity utilization adjustment cost parameter is very small and not significantly different from zero. Since $1/\sigma_\delta$ governs the elasticity of capacity utilization with respect to the return on capital, our estimate of σ_δ implies a large response of utilization to a given movement in capital returns. Even though our estimation is informed by the response of capacity utilization, the model's impulse response lies below the VAR point estimate for much of the impulse response horizon. This finding suggests that this parameter also affects the responses of other variables in the model such as prices through marginal cost dynamics. In unreported results, we confirmed this intuition by re-estimating the parameters without asking the model to match the response of capacity utilization. Under this alternative estimation exercise, we find similar estimates of σ_δ and a marginally better fit for prices.

Turning to investment, we find much larger monthly investment adjustment costs than the quarterly estimates of Christiano, Eichenbaum and Evans (2005). Large adjustment costs imply that firms make incremental investments in their capital stock which generates persistence in the response of investment and overall output. Thus, the model prefers a large value of κ as it helps the model account for the persistence of output and investment we find in the data.[10]

We estimate a significant degree of desired-rate smoothing in the central bank's policy

[9] As Christiano, Eichenbaum and Evans (2005) show, the inclusion of nominal wage rigidity would likely lower our estimate of ω without greatly changing the other estimated parameters or the model's fit of the data.

[10] If we set a tighter prior for κ, Appendix C shows that we find significantly smaller estimates of κ than in our baseline model. Under this alternative prior, the model's fit deteriorates a bit, but not significantly, with the primary difference being the persistence of the investment and output responses.

rule, which is largely consistent with our prior. However, the fact that our estimate doesn't significantly differ from our prior mode suggests that ϕ_r may not be well-identified by our impulse response matching procedure. In Appendix C, we explore alternative priors for ϕ_r and consistently find point estimates of ϕ_r which are very near to the prior mode. With the exception of the size of the initial demand shock, however, we find that all other model parameters and the model's overall fit are not affected if we use an alternative prior for ϕ_r. Since we don't have a strong opinion on the correct size of the initial aggregate demand shock, we find that we can't pin down the degree of history dependence in monetary policy. This result isn't too surprising since we are only informing our estimation procedure with information on monetary policy shocks. Coibion and Gorodnichenko (2012) show that the degree of endogenous interest-rate smoothing is likely better informed by the policy response to non-monetary shocks. However, these additional results show that the overall fit of our model does not rely on a particular assumption about the amount of history dependence in the central bank's policy rule.

5 Quantitative Easing & Forward Guidance Before 2009

To this point, we have identified forward guidance shocks in the data only using policy announcements when the FOMC was constrained by the zero lower bound. During this period, however, the FOMC also conducted several rounds of large-scale asset purchases known as quantitative easing. Similar to forward guidance, the stated goal of these asset purchases was to help stabilize real economic activity and inflation. Announcements regarding these asset-purchase programs, however, often appeared in the same policy statement as changes in the FOMC's forward guidance. Thus, one may be concerned that part of the macroeconomic effects we identify may be due to the asset-purchase programs, not forward guidance.

If asset purchases simply reflect signaling about the path of future short-term rates, then the simultaneous quantitative easing announcements would not affect our results. For example, Krishnamurthy and Vissing-Jorgensen (2011), Woodford (2012), Bauer and Rudebusch (2014), and Bhattarai, Eggertsson and Gafarov (2015) argue that asset purchases acted as a commitment device to reinforce the FOMC's guidance about future policy rates. Of course, in our theoretical model, all economic agents understand that the central bank is fully committed to its policy rule in all states of the world. Therefore, if quantitative easing is simply real-world commitment device then we do not need to worry about disentangling the effects of forward guidance from quantitative easing when bringing the model to the data. However, if asset purchases operate as well through a portfolio-rebalancing channel, then the presence of quantitative easing announcements could bias our estimates of the macroeconomic effects of forward guidance.

To rectify this concern, we now examine the macroeconomic effects of forward guidance announcements prior to the zero lower bound period. Prior to 2009, the FOMC made numerous announcements about the future path of policy rates without any changes in the size or composition of its balance sheet. Using this earlier sample period, we can trace out the macroeconomic effects of a forward guidance shock without worrying about separately identifying the effects of quantitative easing. If we find that the estimated effects prior to and during the zero lower bound period are broadly similar, then this result suggests that the presence of quantitative easing is not significantly affecting our baseline results.

Identifying forward guidance shocks prior to the zero lower bound, however, requires us to isolate changes in the expected path of rates from fluctuations in the current policy rate. Therefore, we use the Gurkaynak, Sack and Swanson (2005) methodology to identify forward guidance shocks in the pre-zero lower bound period. Using measures of both current and expected future stance of monetary policy, Gurkaynak, Sack and Swanson (2005) extract the first two principal components of interest-rate changes around FOMC announcements. After a rotation, they denote the first component the target factor which reflects unexpected changes to the current stance of policy. They denote the second component as the path factor which, similar to our baseline forward guidance shock, captures unexpected changes to the expected path of policy rates. Using the path factor, we can examine the macroeconomic effects of a forward guidance shock both during and prior to the zero lower bound period. Similar to our baseline empirical model, we embed the path factor into a structural vector autoregression to trace out its macroeconomic implications.[11]

We find that forward guidance shocks produce similar macroeconomic effects both before and during the zero lower bound episode. Figure 4 plots the impulse responses to a one standard deviation path factor shock over the 1994-2008 and 2009-2015 sample periods. Both before and during the zero lower bound period, the economy's responses to a forward guidance shock are qualitatively similar: Firms increase their output, raise prices, and invest in new capital. For most variables, the impulse responses are actually quantitatively larger during the pre-zero lower bound period, but are less precisely estimated. Similar to our

[11] In the Appendix, we provide additional details on the construction of the Gurkaynak, Sack and Swanson (2005) target and path factors. During the zero lower bound period, the path factor is highly correlated with our baseline measure of forward guidance shocks from Section 2.

baseline results from Section 2, the peak responses of output and prices are about 10 basis during the zero lower bound period. The robustness of our findings prior to zero lower bound period suggests that quantitative easing (operating through a portfolio-rebalancing channel) is not a key driver of our findings at the zero lower bound.[12]

6 Discussion of Related Literature

6.1 Forward Guidance Puzzle

Our findings suggest no disconnect between the effects of a forward guidance shock in the data and the predictions of a theoretical model of nominal price rigidity. This finding contrasts with recent work by Del Negro, Giannoni and Patterson (2012), which argue that models with nominal rigidities overestimate the expansionary effects of forward guidance. Our alternative conclusion emerges from the size of the forward guidance shock we estimate in the model. In both our empirical evidence and model, a typical expansionary forward guidance shock lowers 12-month ahead futures rates by about 3 basis points. This shock extends the zero lower bound duration by one month in our model. Del Negro, Giannoni and Patterson (2012), however, simulate a much longer one-year extension of the zero lower bound period, which results in a very large expansion in economic activity. These authors argue this increase in activity is implausibly large, and denote their finding the "Forward Guidance Puzzle." However, our estimated model suggests that a one-year exogenous extension requires a highly unlikely 10+ standard deviation shock.[13] Our much smaller exogenous shock produces only modest increases in output and inflation that are consistent with our empirical evidence.

6.2 Elasticity of Output with Respect to Expected Rates

Our conclusions also run counter to Kiley (2016), which argues that output and prices are too responsive to changes in expected rates in standard models with nominal rigidities. However, one may argue that we do not find any disconnect between the model and data because

[12]In related work, Swanson (2016) aims to separately identify the empirical effects of forward guidance and quantitative easing on asset prices. To identify the effects of each policy tool, he *assumes* that forward guidance announcements produce the same movements in asset prices both before and during the zero lower bound period. The robustness of our results across subsamples supports his identifying assumption, at least with respect to the effects on typical macroeconomic variables.

[13]Prior to conducting their forward guidance experiment, Del Negro, Giannoni and Patterson (2012) use overnight-indexed swaps rates to estimate the state of the economy and the expected path of interest rates. However, they do not use these rates to inform the size of the exogenous forward guidance shock they simulate in their model.

our empirical evidence implies an unrealistically large response of output to small changes in expected future interest rates. In the data, we find that a typical forward guidance shock causes a 2.5 basis point movement in one-year ahead expected policy rates, which generates a moderate but sustained economic expansion. In particular, output rises by about 10 basis points at its post-shock peak. Thus, we find an elasticity of the peak response of output with respect to one-year ahead expected policy rates of about 4.3. Using established results in the prior literature, we want to know whether this elasticity is empirically reasonable.

Thus, we compare our findings with the previous work of Romer and Romer (2004) and Christiano, Eichenbaum and Evans (2005) on the effects of conventional monetary policy shocks. Specifically, we use the empirical VAR models in those papers to compute the same elasticity, the peak response of output with respect to one-year ahead expected interest rates. Since we focus on the elasticity of output to expected rather than current policy rates, we use their estimated VAR models to measure expectations of future policy rates following a conventional monetary policy shock. In the monthly VAR model of Romer and Romer (2004), we measure one-year ahead expected policy rates using the point estimate of the policy rate 12 periods after a monetary policy shock. Similarly, we use the response of the federal funds rate after 4 periods in the quarterly model of Christiano, Eichenbaum and Evans (2005) as our measure of one-year ahead policy expectations. Figure 5 shows the responses of output and interest rates in each of the three models. The diamonds reflect the points used to compute the elasticity of interest.

Our baseline empirical results imply very similar elasticities to the findings from the previous conventional policy shock literature. In Romer and Romer's (2004) model, the elasticity of the peak response of output with respect to one-year ahead expected future policy rates is 3.9. Similarly, the VAR model of Christiano, Eichenbaum and Evans (2005) implies an elasticity of 4.9. Thus, our estimated elasticity of output with respect to expected policy rates of 4.3 after a forward guidance shock is in the range of other estimates from the previous conventional policy shock literature. In addition, we can also compute the elasticity of the peak response of prices with respect to one-year ahead expected policy rates. Our empirical VAR generates a price elasticity of 4.0, which is also between the values of Romer and Romer's model (6.2) and the results of Christiano, Eichenbaum, and Evans (3.5).

6.3 Other Related Literature

Recent papers by McKay, Nakamura and Steinsson (2014) and Kaplan, Moll and Violante (2016) also argue that standard representative-agent macroeconomic models overstate the effects of forward guidance. McKay, Nakamura and Steinsson (2014) focus specifically on the implications of the linearized consumption Euler equation for a given path of real interest rates. Holding all other real interest rates fixed, they simulate an exogenous decline in real interest rates for a single period in the future. They show that the effects on household consumption and prices increase as the real rate shock moves several years into the future. They argue that these effects are unrealistic, so they introduce idiosyncratic household risk and borrowing constraints to temper the responses of consumption and prices.

For the typical one- to two-year ahead guidance provided by the FOMC, we find that a standard representative-agent model is a good approximation to the actual economy following a forward guidance shock. While households and firms absolutely consider risk and borrowing constraints when making their decisions in reality, our results suggests that these features may not be strictly necessary to model the implications for typical macroeconomic aggregates. Thus, we believe that the same models Christiano, Eichenbaum and Evans (2005) and others use to study the effects of conventional monetary policy shocks remain useful in studying forward guidance shocks at the zero lower bound.

Recent work by Gertler and Karadi (2015) also examines the effects of monetary policy shocks. Similar to our work, these authors measure policy shocks using high-frequency changes in futures rates around policy announcements. However, they then use these shocks as external instruments to estimate the effects of a policy shock on a variety of macroeconomic and financial variables. Our work differs from theirs along two key margins. First, since we focus primarily on the zero lower bound period, we are able to trace out the effects of a forward guidance shock without any change in the current policy rate. Gertler and Karadi (2015) cannot separately decompose the effects of a change in the current policy rate versus the expected path of policy. Second, our framework allows us to examine additional policy indicators, such as two-year ahead futures rates and the Gurkaynak, Sack and Swanson (2005) path factor, which are generally unavailable in their external instruments procedure.[14]

[14]Specifically, Gertler and Karadi (2015) find that the Gurkaynak, Sack and Swanson (2005) path factor is not a strong instrument for the monthly reduced-form VAR residuals of the one-year ahead bond yield. In addition, they do not find any strong instruments for the two-year bond yield as a policy indicator.

Our paper is also related to Nakamura and Steinsson (2015), which uses high-frequency responses of interest rates to estimate monetary non-neutrality. The authors estimate the effects of FOMC announcements on various nominal and real interest rates. Then, they estimate a medium-scale macroeconomic model such that the impact effects on the model-implied nominal and real yield curves following a conventional monetary policy shock are consistent with their high-frequency evidence. They measure the degree of monetary non-neutrality as the ratio of the cumulative response of output to the cumulative response of inflation. They estimate this ratio to be 3.8, which implies output moves almost four times as much as inflation after a monetary shock. Using their measure, our baseline forward guidance shock produces a ratio less than one, which is closer to the model-implied value of Christiano, Eichenbaum and Evans (2005).

7 Conclusions

We draw several conclusions from our results. First, an unexpected decline in the path of policy rates at the zero lower bound produces a sustained economic expansion. Unlike the previous literature, we show that these estimated effects of forward guidance in the data are fully consistent with a standard macroeconomic model with nominal rigidities. Thus, we find no disconnect between the empirical effects of forward guidance shocks and the predictions from a textbook model of monetary policy. Our conclusion rests on appropriately calibrating the size of the forward guidance shock to simulate in the model. Finally, we argue that the same models economists use to study the effects of conventional monetary policy shocks remain useful in studying forward guidance shocks at the zero lower bound.

References

Barakchian, S. Mahdi, and Christopher Crowe. 2013. "Monetary Policy Matters: Evidence from New Shocks Data." *Journal of Monetary Economics*, 60(8): 950 – 966.

Bauer, Michael D, and Glenn D Rudebusch. 2014. "The Signaling Channel for Federal Reserve Bond Purchases." *International Journal of Central Banking*, 10(3): 233–289.

Bhattarai, Saroj, Gauti B. Eggertsson, and Bulat Gafarov. 2015. "Time Consistency and the Duration of Government Debt: A Signalling Theory of Quantitative Easing." Working Paper.

Calvo, Guillermo A. 1983. "Staggered Prices in a Utility-Maximizing Framework." *Journal of Monetary Economics*, 12(3): 383–398.

Campbell, Jeffrey R., Charles L. Evans, Jonas D.M. Fisher, and Alejandro Justiniano. 2012. "Macroeconomic Effects of Federal Reserve Forward Guidance." *Brookings Papers on Economic Activity*, 44(1): 1–80.

Christiano, Lawrence J., Martin Eichenbaum, and Charles L. Evans. 2005. "Nominal Rigidities and the Dynamic Effects of a Shock to Monetary Policy." *Journal of Political Economy*, 113(1): 1–45.

Christiano, Lawrence J., Martin S. Eichenbaum, and Mathias Trabandt. 2016. "Unemployment and Business Cycles." *Econometrica*, 84(4): 1523–1569.

Christiano, Lawrence J., Mathias Trabandt, and Karl Walentin. 2010. "DSGE Models for Monetary Policy Analysis." In *Handbook of Monetary Economics*. Vol. 3 of *Handbook of Monetary Economics*, , ed. Benjamin M. Friedman and Michael Woodford, Chapter 7, 285–367. Elsevier.

Cogley, Timothy, Giorgio E. Primiceri, and Thomas J. Sargent. 2010. "Inflation-Gap Persistence in the US." *American Economic Journal: Macroeconomics*, 2(1): 43–69.

Coibion, Olivier, and Yuriy Gorodnichenko. 2012. "Why are target interest rate changes so persistent?" *American Economic Journal: Macroeconomics*, 4(4): 126–162.

Coleman, Wilbur John. 1990. "Solving the Stochastic Growth Model by Policy Function Iteration." *Journal of Business & Economic Statistics*, 8(1): 27–29.

Davig, Troy. 2004. "Regime-Switching Debt and Taxation." *Journal of Monetary Economics*, 51(4): 837–859.

Davig, Troy, and Taeyoung Doh. 2014. "Monetary policy regime shifts and inflation persistence." *Review of Economics and Statistics*, 96(5): 862–875.

Del Negro, Marco, Marc Giannoni, and Christina Patterson. 2012. "The Forward Guidance Puzzle." Working Paper.

Eggertsson, Gauti B., and Michael Woodford. 2003. "The Zero Lower Bound on Interest Rates and Optimal Monetary Policy." *Brookings Papers on Economic Activity*, 1: 139–211.

Eichenbaum, Martin, and Jonas D.M. Fisher. 2007. "Estimating the frequency of price re-optimization in Calvo-style models." *Journal of Monetary Economics*, 54(7): 2032 – 2047.

Ferson, Wayne E, and George M Constantinides. 1991. "Habit persistence and durability in aggregate consumption: Empirical tests." *Journal of Financial Economics*, 29(2): 199–240.

Gali, Jordi, and Mark Gertler. 1999. "Inflation dynamics: A structural econometric analysis ." *Journal of Monetary Economics*, 44(2): 195 – 222.

Gertler, Mark, and Peter Karadi. 2015. "Monetary Policy Surprises, Credit Costs, and Economic Activity." *American Economic Journal: Macroeconomics*, 7(1): 44–76.

Guerrieri, Luca, and Matteo Iacoviello. 2015. "OccBin: A Toolkit for Solving Dynamic Models with Occasionally Binding Constraints Easily." *Journal of Monetary Economics*, 70: 22–38.

Gurkaynak, Refet S, Brian Sack, and Eric Swanson. 2005. "Do Actions Speak Louder Than Words? The Response of Asset Prices to Monetary Policy Actions and Statements." *International Journal of Central Banking*, 1(1): 55–93.

Ireland, Peter N. 2003. "Endogenous Money or Sticky Prices." *Journal of Monetary Economics*, 50: 1623–1648.

Ireland, Peter N. 2011. "A New Keynesian Perspective on the Great Recession." *Journal of Money, Credit, and Banking*, 43(1): 31–54.

Kaplan, Greg, Benjamin Moll, and Giovanni L. Violante. 2016. "A Note on Unconventional Monetary Policy in HANK." Working Paper.

Keen, Benjamin D., Alexander W. Richter, and Nathaniel A. Throckmorton. 2015. "Forward Guidance and the State of the Economy." Working Paper.

Kiley, Michael T. 2016. "Policy Paradoxes in the New Keynesian Model." *Review of Economic Dynamics*, 21: 1–15.

Koop, Gary, and Dimitris Korobilis. 2010. *Bayesian Multivariate Time Series Methods for Empirical Macroeconomics.* Now Publishers Inc.

Krishnamurthy, Arvind, and Annette Vissing-Jorgensen. 2011. "The Effects of Quantitative Easing on Interest Rates: Channels and Implications for Policy." *Brookings Papers on Economic Activity*, 43(2): 215–287.

McKay, Alisdair, Emi Nakamura, and Jón Steinsson. 2014. "The Power of Forward Guidance Revisited." Working Paper.

Nakamura, Emi, and Jón Steinsson. 2008. "Five Facts about Prices: A Reevaluation of Menu Cost Models." *Quarterly Journal of Economics*, 123(4): 1415–1464.

Nakamura, Emi, and Jón Steinsson. 2015. "High Frequency Identification of Monetary Non-Neutrality." Working Paper.

Reifschneider, David, and John C. Williams. 2000. "Three Lessons for Monetary Policy in a Low-Inflation Era." *Journal of Money, Credit, and Banking*, 32(4): 936–966.

Romer, Christina D., and David H. Romer. 2004. "A New Measure of Monetary Shocks: Derivation and Implications." *American Economic Review*, 94(4): 1055–1084.

Sims, Christopher A., and Tao Zha. 1999. "Error Bands for Impulse Responses." *Econometrica*, 67(5): 1113–1155.

Swanson, Eric T. 2016. "Measuring the Effects of Unconventional Monetary Policy on Asset Prices." Working Paper.

Taylor, John B. 1993. "Discretion Versus Policy Rules in Practice." *Carnegie-Rochester Conference Series on Public Policy*, 39: 195–214.

Woodford, Michael. 2012. "Methods of Policy Accommodation at the Interest-Rate Lower Bound." *The Changing Policy Landscape: 2012 Jackson Hole Symposium.*

Table 1: Calibrated Model Parameters

Parameter	Description	Calibrated Value
β	Household Discount Factor	0.9983
Π	Steady State Inflation Rate	$1.02^{\frac{1}{12}}$
δ_0	Steady State Depreciation	0.1 / 12
δ_1	First-Order Utilization Parameter	$1/\beta - 1 + \delta_0$
η	Inverse Frisch Labor Supply Elasticity	0.5
ξ	Utility Function Constant	58.43
θ	Elasticity of Substitution Intermediate Goods	6.0
α	Capital Share in Production Function	0.33
ϕ_π	Central Bank Response to Inflation	1.5
ϕ_y	Central Bank Response to Output	0.1
ρ_a	Preference Shock Persistence	0.95
σ^a	Std. Dev. of Preference Shock	0.005

Table 2: Estimated Model Parameters

		Prior			Posterior	
Parameter	Description	Distribution	Mode	Std. Dev.	Mode	Std. Dev.
b	Habit Persistence	Beta	0.50	0.25	0.7784	0.0211
ω	Calvo Probability	Beta	0.93	0.02	0.9535	0.0005
χ	Degree of Lagged Indexation	Beta	0.50	0.25	0.2735	0.0099
ϕ_r	Policy Rate Smoothing	Beta	0.75	0.25	0.7834	0.0078
κ	Investment Adjustment	Gamma	2.48	60.0	76.2051	4.6839
σ_δ	Capacity Utilization Curvature	Gamma	0.01	60.0	1.4811×10^{-5}	0.0001
ρ_ν	Policy Shock Persistence	Beta	0.50	0.25	0.9545	0.0005
$1200 \times \sigma_\nu$	Std. Dev. of Policy Shock	Gamma	25.0	1200	0.0917	0.0041

Table 3: Variance of Forecast Errors Explained by Monetary Policy Shocks

Output

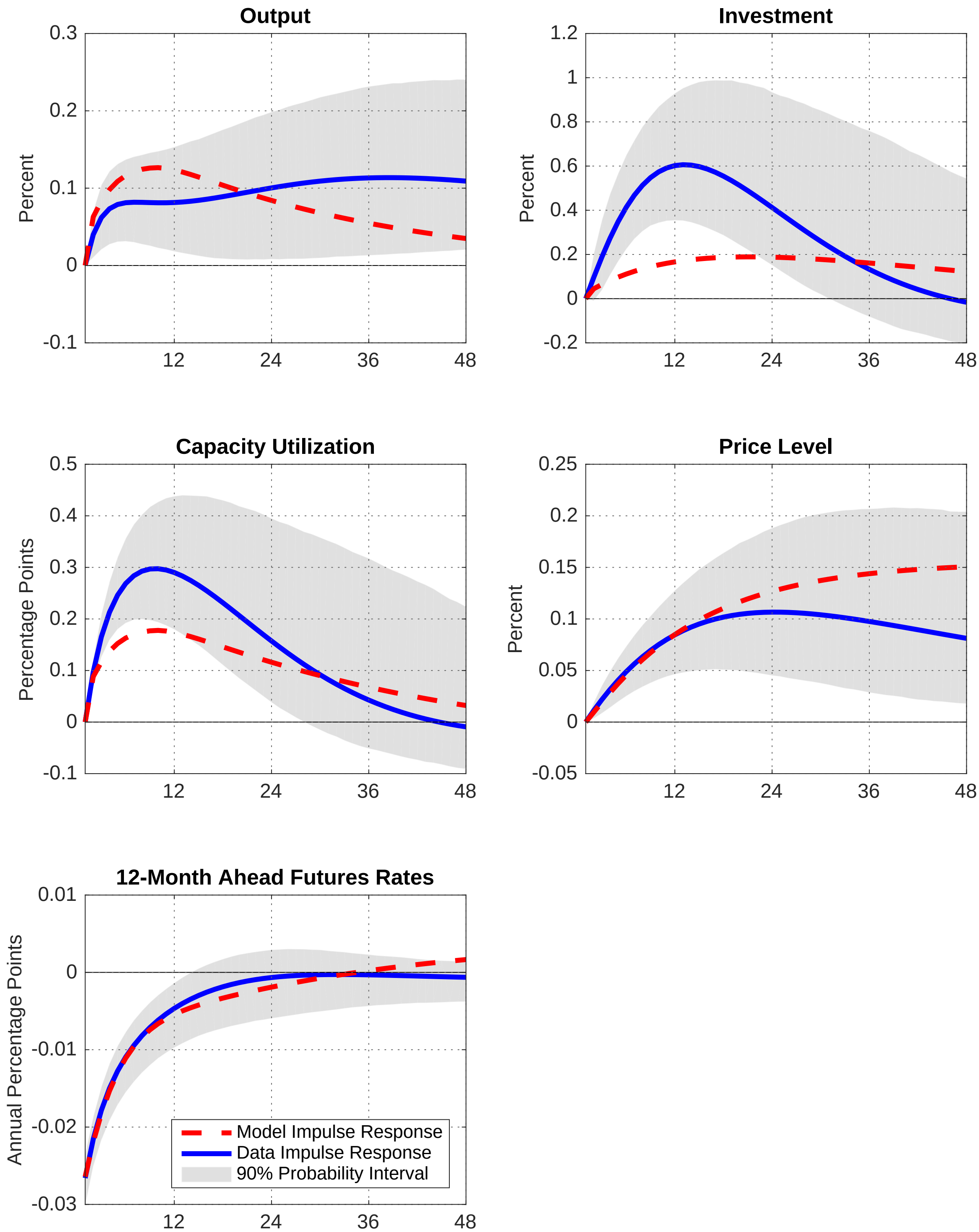
Model	1-Year Horizon	2-Year Horizon	5-Year Horizon
Baseline VAR	9	16	30
	(1, 21)	(2, 34)	(3, 52)
Romer & Romer (2004)	7	25	22
	(1, 18)	(6, 47)	(9, 48)
Christiano, Eichenbaum, & Evans (2005)	15	41	26
	(5, 24)	(21, 47)	(11, 32)

Price Level

Model	1-Year Horizon	2-Year Horizon	5-Year Horizon
Baseline VAR	19	35	45
	(5, 34)	(9, 52)	(7, 62)
Romer & Romer (2004)	0	5	80
	(0, 7)	(1, 21)	(48, 90)
Christiano, Eichenbaum, & Evans (2005)	1	1	14
	(0, 5)	(0,6)	(2, 26)

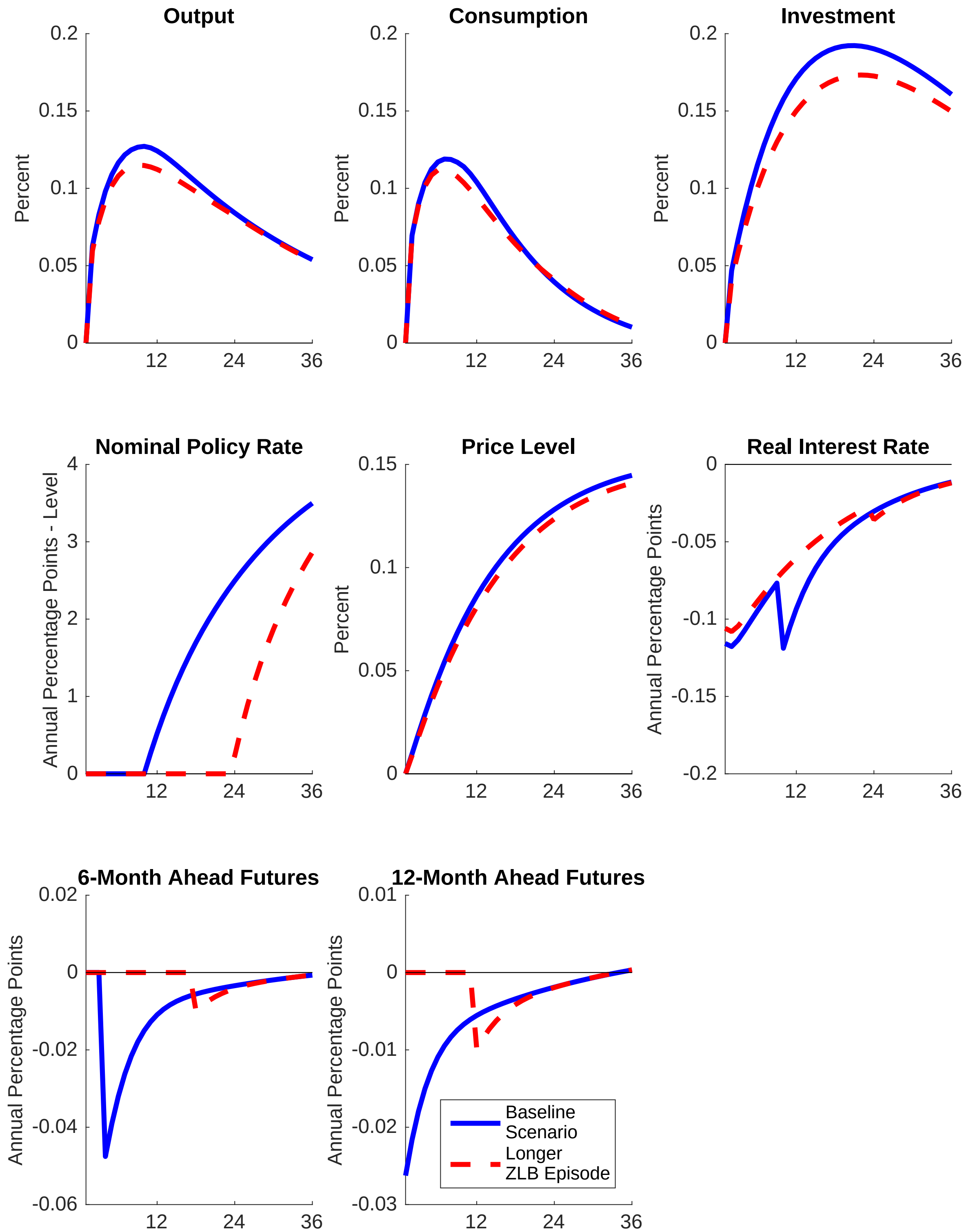
Notes: Numbers in parentheses are the 90% confidence interval. For comparison with our baseline results, we estimate the model of Christiano, Eichenbaum, & Evans (2005) using the price level in the VAR, rather than the inflation rate. Romer & Romer (2004) proxy output at a monthly frequency using industrial production.

Figure 1: Empirical & Model-Implied Impulse Responses to Forward Guidance Shock



Note: The solid blue lines denote the empirical point estimate to a one standard deviation shock and the shaded areas denote the 90% probability interval of the posterior distribution. The red dashed line denotes the model-implied impulse response.

Figure 2: Role of the Initial Demand Shock



Note: The plot of the nominal interest rate reflects its level after the forward guidance shock.

Figure 3: Effects of Forward Guidance Shock Persistence

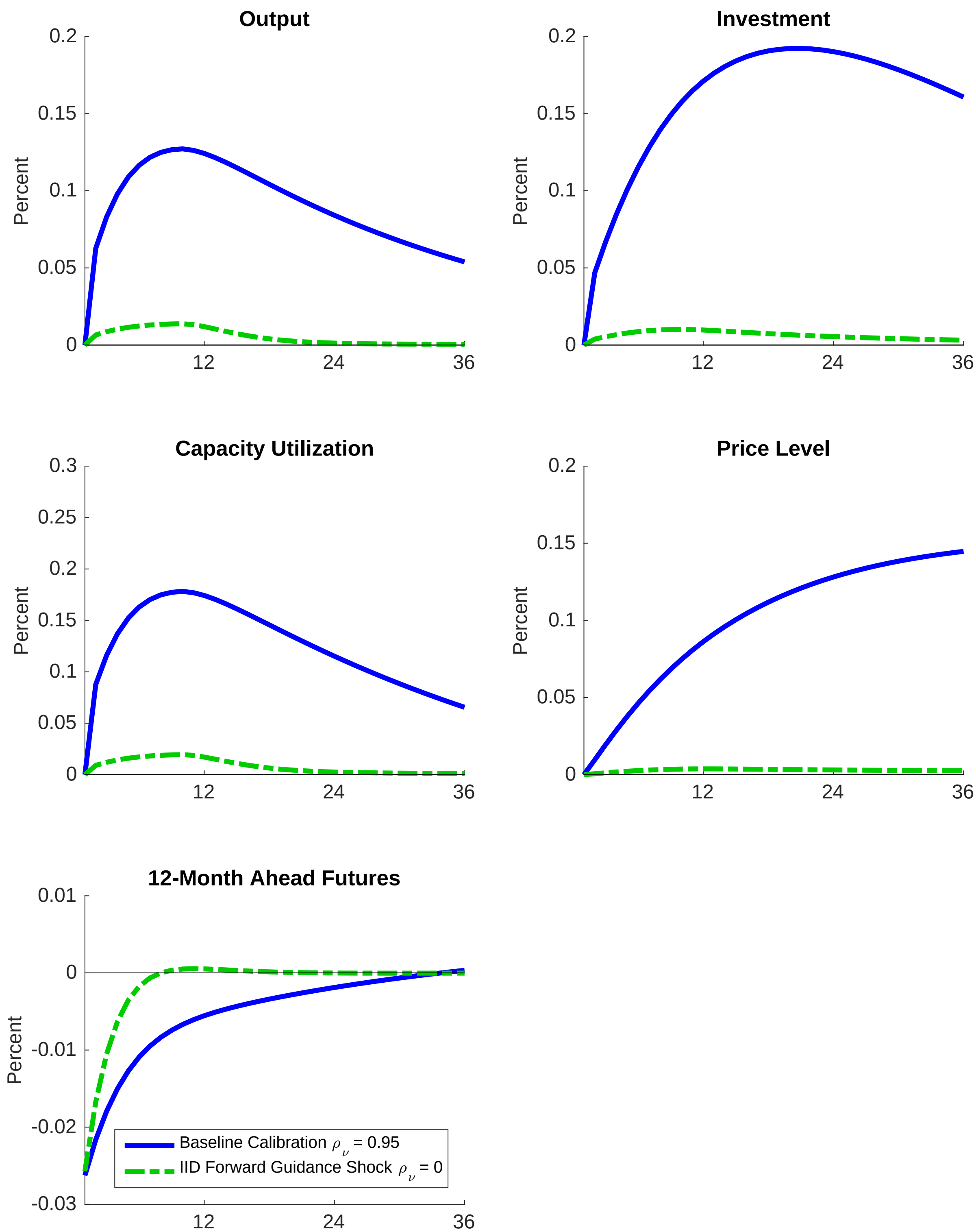
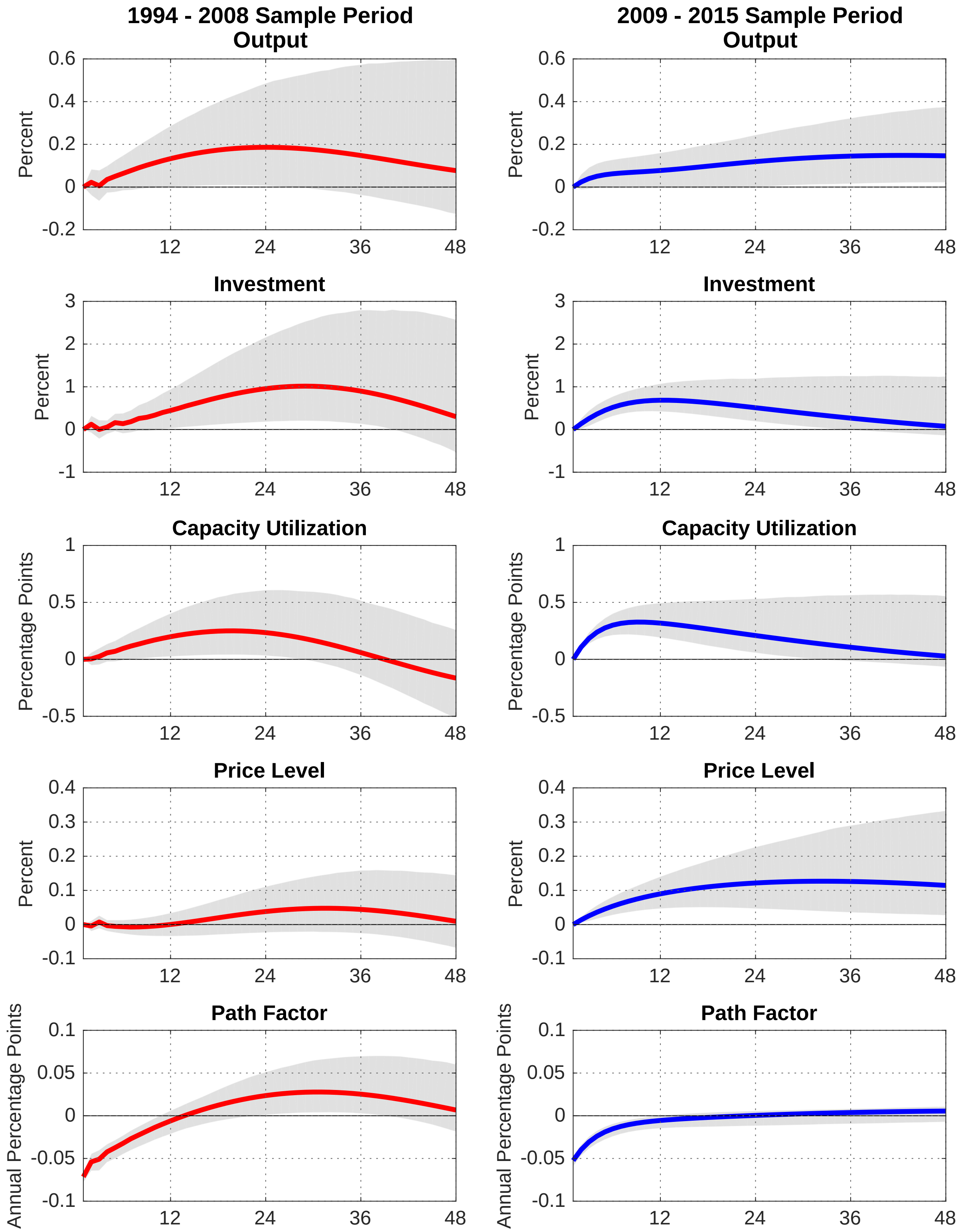
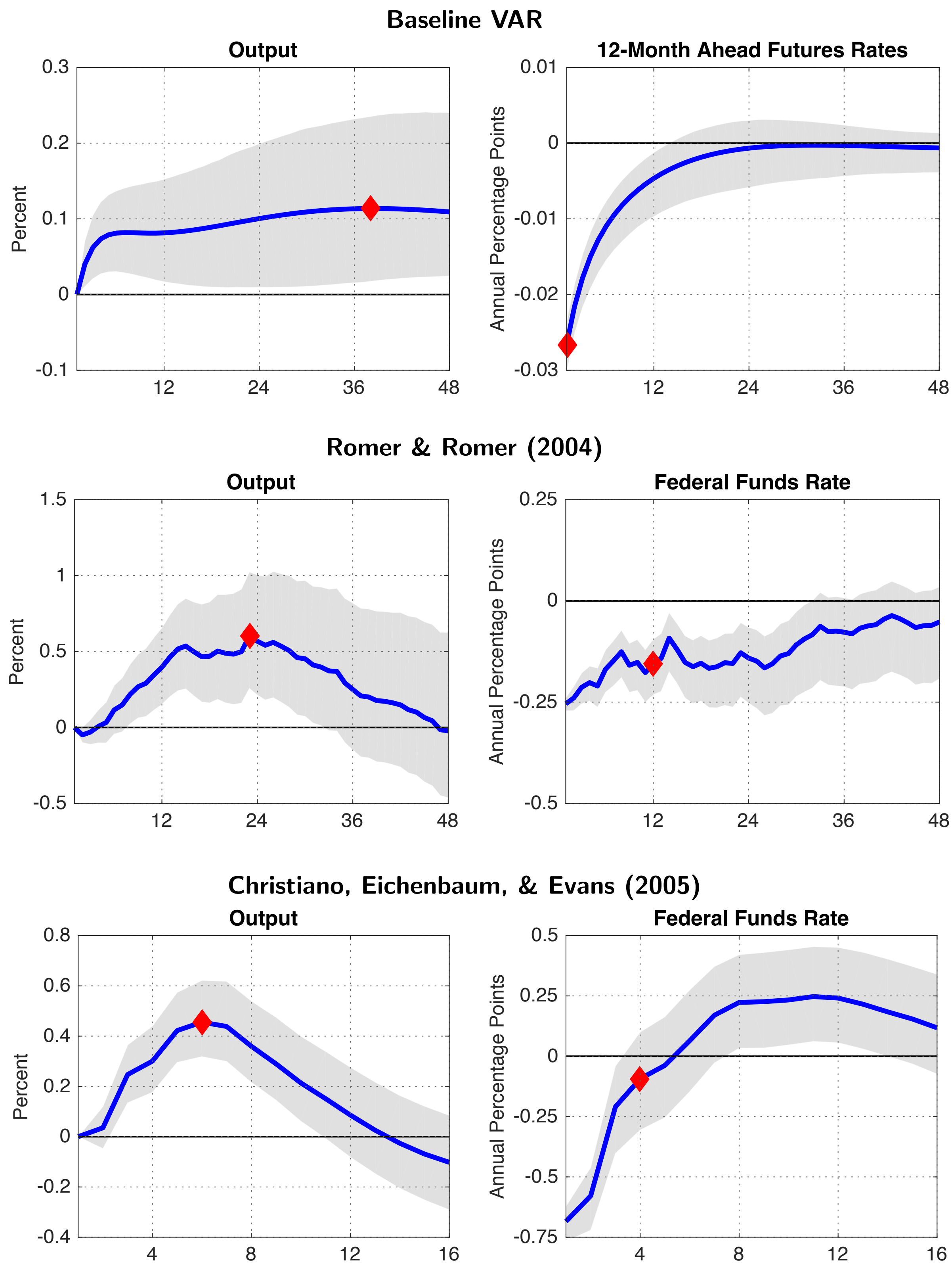


Figure 4: Empirical Impulse Responses Before & During the Zero Lower Bound Period



Note: The solid lines denote the point estimate to a one standard deviation shock and the shaded areas denote the 90% probability interval of the posterior distribution. Each column represents the impulse responses from a different empirical model.

Figure 5: Elasticity of Output with Respect to Expected Policy Rates



Note: The solid lines denote the point estimate to a one standard deviation shock and the shaded areas denote the 90% probability interval of the posterior distribution. Each row represents the impulse responses from a different empirical model. The diamonds denote the point estimates used in calculating the elasticity of output with respect to one-year ahead expected policy rates. Romer & Romer (2004) proxy output at a monthly frequency using industrial production.