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How Optimal Was U.S. Monetary Policy at the Zero Lower Bound?*

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Abstract

In theory, the zero lower bound on nominal interest rates can generate substantial downward pressure on longer-term inflation expectations. We use data on interest rate options and inflation compensation to estimate the degree to which the probability that the zero lower bound binds in the future has weighed on inflation expectations in the United States. Over the 2008-2019 period, we estimate that the zero lower bound imparted only a small drag on longer-term inflation expectations of around 10 basis points. We argue that the Federal Reserve's use of forward guidance and large-scale asset purchases largely offset the potential disinflationary effects of the zero lower bound, even prior to formally adopting an average inflation targeting framework.

JEL Classification: E32, E52

Keywords: Monetary Policy, Inflation Expectations, Zero Lower Bound, Forward Guidance, Asset Purchases

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1 Introduction

Economists and policymakers have argued that the zero lower bound on nominal interest rates can significantly constrain the central bank's ability to achieve its inflation objective. Predictions from theoretical models support this argument. Early theoretical work by Reifschneider and Williams (2000) shows that the reduced capacity to offset adverse shocks at the zero lower bound lowers average inflation under conventional Taylor (1993)-type policy rules. In such models, longer-term inflation expectations will erode on the belief that inflation will be persistently lower in the presence of the zero lower bound, reinforcing the disinflationary effects of the lower bound constraint. Therefore, in an environment where monetary policy is expected to be constrained by the zero lower bound, even a central bank that is committed to achieving its inflation target can fall short of its inflation objective. In its most recent Statement on Longer-Run Goals and Strategy, the Federal Open Market Committee (FOMC) acknowledged that more frequent encounters with the zero lower bound posed a downside risk to inflation and employment outcomes.[1]

However, previous research shows that policymakers can reduce the disinflationary effects of the zero lower bound using forward guidance about future interest rates or large-scale asset purchases (LSAPs). With regards to forward guidance, Reifschneider and Williams (2000) and Eggertsson and Woodford (2003) show that monetary policy can reduce or eliminate this deflationary force if it communicates an intention to follow more accommodative policy in the future in response to an economic downturn today. Recent work by Sims and Wu (2020) and Sims, Wu and Zhang (2023) highlights that LSAPs can significantly mitigate the costs imposed by the zero lower bound constraint. More generally, this literature has highlighted that optimal policy outcomes can largely be achieved in the face of the zero lower bound with the use of these unconventional policy tools.

In practice, the Federal Reserve actively used both forward guidance and LSAPs to pursue their congressional mandates in the face of the zero lower bound. Given the power of these tools in theoretical settings, it remains an open question whether these tools were sufficient in practice to overcome the deleterious effects that the lower bound on nominal interest rates can have on inflation expectations.

In this paper, we estimate the extent to which the zero lower bound has weighed on

[1] The FOMC revised its Statement on Longer-Run Goals and Monetary Policy Strategy in August 2020 and is available at `www.federalreserve.gov/monetarypolicy/files/FOMC_LongerRunGoals.pdf`.

longer-term inflation expectations. Using a theoretical model, we first derive testable predictions under alternative monetary policies at the zero lower bound. Building on Mertens and Williams (2019, 2021), we show that an exogenous increase in the probability of encountering the zero lower bound significantly lowers longer-term inflation expectations if policymakers follow a standard Taylor (1993)-type policy rule. Instead, if the central bank turns to forward guidance or asset purchases when the zero lower bound becomes binding, then a higher likelihood of a binding zero lower bound constraint may have little to no effect on longer-run inflation expectations. These theoretical results show that the degree to which the zero lower bound weighs on inflation expectations is an empirical question whose answer crucially depends on the perceptions of the conduct of monetary policy.

Guided by these testable predictions, we then use a two-step procedure to evaluate the disinflationary effect that the zero lower bound imparted on the U.S. economy. First, we use interest rate options to construct a daily measure of the market-implied probability of being at the zero lower bound six quarters in the future. We regress the daily change in this probability on a large set of daily macroeconomic data releases and monetary policy shocks. The unexplained residuals from this first-stage regression provide variation in the probability of hitting the zero lower bound that is unrelated to the current state of the macroeconomy or unexpected changes in monetary policy. Then, we regress the daily change in far-forward measures of inflation compensation on this exogenous variation in the probability of hitting the zero lower bound. A large negative coefficient in this second-stage regression would suggest an increase in the probability of hitting the zero lower bound significantly lowers longer-term inflation expectations.

However, we find only a small drag on inflation expectations due to the zero lower bound over the 2008-2019 period. We estimate that a 10 percentage point increase in the probability of encountering the zero lower bound reduces longer-term inflation expectations by just 3 basis points. On average, from 2008 through 2019, financial markets placed approximately a 30 percent probability of encountering the zero lower bound six quarters in the future. Therefore, based on our estimates, the presence of the zero lower bound reduced longer-term inflation expectations by a modest 10 basis points from 2008 through 2019.

Returning to our theoretical model, we show that this empirical evidence is consistent with a central bank that uses forward guidance, asset purchases, or a mix of the two, to help stabilize the economy at the zero lower bound. Specifically, forward guidance, operationalized with a history-dependent policy rule of the form originally suggested by Reifschneider and Williams (2000), or an asset purchase policy rule, as in the model of Sims, Wu and Zhang (2023), can reproduce our empirical estimate of the modest effect of the zero lower bound on inflation expectations. Implicitly, our findings suggest that market participants view these less conventional policy tools as effective substitutes for reductions in the federal funds rate in the presence of a binding zero lower bound constraint.

Finally, our results have implications for the potential effects of the FOMC's revamped policy framework. In its 2020 Statement on Longer-Run Goals and Strategy, the FOMC formally adopted an average-inflation targeting framework which stated the Committee will allow inflation to overshoot its 2% objective if it has run persistently below target to offset the potential disinflation imparted by the zero lower bound. Mertens and Williams (2019), Bernanke, Kiley and Roberts (2019) and others show that adopting such a policy can indeed lead to better outcomes for the economy when compared with a discretionary policy. However, our empirical results suggest that prior to 2020 the FOMC had already achieved many of the gains of history-dependent policy through its use of forward guidance and balance sheet policies. Thus, echoing Clarida (2019), our results suggest that the new framework is likely more evolutionary than revolutionary in terms of its effects on inflation expectations.

Several other works in the prior literature also discuss the possible disinflationary effects of the zero lower bound. Kiley and Roberts (2017) documents that a higher likelihood of a binding zero lower bound constraint can lead to lower average inflation under standard Taylor (1993)-type policy rules. The key contribution in our paper is to use information from options prices to provide new empirical estimates of the potential disinflationary effect of the zero lower bound. Our paper is also related to Gust et al. (2017), Plante, Richter and Throckmorton (2018), and Hills, Nakata and Schmidt (2019) which either estimate or calibrate dynamic structural models of the U.S. economy. These papers attribute sizable negative effects from the zero lower bound on US macroeconomic aggregates. For example, Hills, Nakata and Schmidt (2019) argue that the zero lower bound leads inflation to undershoot the Federal Reserve's 2 percent inflation target by a full 50 basis points. However, all of these papers employ models that fully abstract from the role that the Fed's balance sheet may have played in offsetting the zero lower bound. Given the extensive use of LSAPs since 2008, this abstraction could lead researchers to overstate the adverse effects of the zero lower bound. Moreover, since these papers use the same policy rule to characterize history dependence both at and away-from the zero lower bound, traditional interest rate smoothing could be confounded with smoothing in the desired policy rate, a form of history dependence that can help account for the FOMC's use of forward guidance at the zero lower bound. In contrast, our empirical strategy overcomes these shortcomings by relying on real-time market perceptions of balance sheet and forward guidance policies at the zero lower bound.

Our paper closely relates to Mertens and Williams (2021) who also use a theoretical model and financial market data to analyze the effects of the zero lower bound in the United States. Building on Benhabib, Schmitt-Grohè and Uribe (2001), they show that models with a zero lower bound on nominal rates feature both a "target" equilibrium, in which the zero lower bound binds only occasionally and inflation expectations are anchored at the central bank's inflation target, and a "liquidity trap" equilibrium, where the zero lower bound almost always binds and inflation expectations fall below the central bank's inflation target. Using data on far-forward (e.g. 5 years ahead) interest rate and inflation options, they find that the market-implied distribution of future interest rates and inflation is consistent with the target equilibrium.

Our paper builds on the analysis of Mertens and Williams (2021) in several dimensions. First, we add empirical evidence with new data over a longer sample that includes the entire seven-year span that the federal funds rate was pegged at the zero lower bound (2008-2015).[2] At a six-quarter ahead horizon, we document that the market-implied probability of being at the zero lower bound features a modest unconditional probability of around 30% from 2008-2019, providing further evidence in favor of the target equilibrium. Second, our empirical strategy differs from Mertens and Williams (2021) as we aim to take account of events that could otherwise bias the estimated importance of the lower bound on inflation expectations. For instance, we use Swanson's (2021) measures of FOMC policy surprises to control for FOMC announcements which may exogenously increase (or decrease) both the probability of the zero lower bound and inflation expectations. Third, our work helps us further understand why the presence of the zero lower bound has had only a small effect on long-run inflation expectations in the United States. Mertens and Williams (2021) conjecture that the Federal Reserve's use of forward guidance and asset purchases might explain this empirical finding. Using a theoretical model that explicitly accounts for these unconventional policy tools, we show that active use of forward guidance and asset purchases in the model can indeed account for the modest disinflationary effects from the zero lower bound observed in the data.

[2] Mertens and Williams's (2021) analysis of inflation is over a relatively shorter sample (2011-2016) because they rely primarily on inflation caps and floors.

2 Testable Predictions Under Alternative Policies

2.1 Model Setup

In this section, we use a simple but microfounded model of the macroeconomy to derive testable predictions under alternative monetary policies at the zero lower bound. Specifically, we use the four-equation New Keynesian model developed by Sims, Wu and Zhang (2023). This model builds on prior work from Galí (2015) and many others in providing a framework for macroeconomic analysis in terms of the economy's output, inflation, and the nominal policy rate. However, the model of Sims, Wu and Zhang (2023) also allows asset purchases by the central bank to affect macroeconomic outcomes.

Starting from the optimizing behavior of households and firms, Sims, Wu and Zhang (2023) show that we can derive the following first-order approximation of the macroeconomy:

$$x_t = E_t\, x_{t+1} - \frac{1-z}{\sigma}\Big(i_t - E_t\,\pi_{t+1} - r_t^n\Big) - z * b^{cb}\Big(E_t\, qe_{t+1} - qe_t\Big) \tag{1}$$

$$\pi_t = \beta\, E_t\,\pi_{t+1} + \kappa\, x_t - \frac{z\gamma\sigma}{1-z}\, b^{cb}\, qe_t \tag{2}$$

where x_t denotes the gap between actual and potential output, π_t represents inflation in deviations from the central bank's objective, and i_t denotes the actual nominal policy rate in deviations from its steady-state value. r_t^n is the economy's natural rate of interest which captures fundamental changes in firm productivity or other demand shocks. qe_t denotes the real market value of the central bank's longer-term bond portfolio. κ denotes the response of inflation to changes in the output gap, commonly referred to as the slope of the New-Keynesian Phillips curve. The parameter γ signifies the elasticity of inflation with respect to firm marginal costs and σ is the household's intertemporal elasticity of substitution. z denotes the share of the "children" or borrowers in the Sims, Wu and Zhang (2023) model and b^{cb} controls the steady-state bond holdings of the central bank.

The parameter β represents the household's discount factor which controls the steady-state real interest rate for this economy. All else equal, a higher β implies lower average interest rates which causes the zero lower bound to bind more often. Since the model in Equations (1) and (2) is linearized around the non-stochastic steady state, the zero lower bound will bind whenever the nominal rate i_t falls below $1 - 1/\beta$. We denote the central bank's desired interest rate as i_t^d and the actual policy rate subject to the lower bound as i_t.

In the original formulation of the Sims, Wu and Zhang (2023) model, the parameter β is constant. Therefore, their model (for a given set of parameters) does not generate any permanent variation in the probability that the zero lower bound. Therefore, we use their model but vary the calibration of β to generate variation in the probability that the zero lower bound affects the economy. We interpret this variation as permanent changes in longer-run interest rates that are unrelated to the cyclical state of the economy which is instead captured by r_t^n. This variation in β could be further micro-founded as permanent changes in household discount factors.

We solve the model in Equations (1) and (2) using a global solution method known as policy function iteration and solve the model over a variety of values for β. Following Sims, Wu and Zhang (2023), we set $z = 0.33$, $\sigma = 1$, and $\gamma = 0.086$.[3] We calibrate κ to a standard value of 0.03. As in Mertens and Williams (2021), we initially assume $\varepsilon_t^r \sim N(0, \sigma^r)$. To calibrate the volatility of the natural rate process, we estimate a first-order autoregressive model on the estimated natural rate series of Cúrdia et al. (2015). We set $\sigma^r = 0.00237$ which equals the volatility of the shock process from that simple time-series model. After the presentation of our baseline results, we will further discuss the calibration of the shock process and its implications (including the inclusion of persistence in the shock process).

To generate predictions in the model which we can later test in the data, we use the model solution to generate inflation forwards and forward-looking probabilities that the zero lower bound will bind in the future. Specifically, we calculate 1-40 quarters ahead expected inflation forwards and 1-6 quarter ahead zero lower bound probabilities where n denotes the horizon in quarters.

$$\pi_t^{e,n} = E_t \, \pi_{t+n} \tag{3}$$

$$p_t^{ZLB,n} = E_t \mathbb{1}_{i_{t+n}^d \leq i_{t+n}} \tag{4}$$

where $\mathbb{1}_{i_{t+n}^d \leq i_{t+n}}$ is an indicator function which takes a value of one in a state in which the zero lower bound binds and zero otherwise.

2.2 Implications of a Conventional Policy Rule

We begin our analysis assuming the monetary authority sets its desired policy rate according to the following rule:

$$i_t^d = r_t^n + \phi_\pi \pi_t. \tag{5}$$

[3] Sims, Wu and Zhang (2023) also introduce credit shocks in their model. These additional shocks are not necessary for generating our main results so we abstract from them. Thus, we set $b^{cb} = 1$ for simplicity.

Under this rule, the central bank uses its conventional short-term policy rate to offset cyclical fluctuations in the economy by tracking the natural rate of interest.[4] However, policymakers do not actively use forward guidance or asset purchases to help stabilize the economy at the zero lower bound ($qe_t = 0$ each period). When policymakers are unconstrained by the zero lower bound, offsetting any fluctuations in the natural rate fully stabilizes the output gap and inflation. However, once the natural rate falls below zero, policymakers can no longer track the natural rate and the economy experiences adverse fluctuations.

Households and firms understand that, if the zero lower bound is more likely to bind, then they are more likely to experience adverse fluctuations in the future. To illustrate this idea, we first pick a low value for β such that the zero lower bound hardly ever binds, set the natural rate process equal to its steady-state value ($r_t^n = 0 \, \forall t$), and iterate the model forward. In period 4, we simulate a permanent change in β such that the zero lower bound now binds roughly 10% of the time on average. The blue line in Figure 1 illustrates the responses of the economy for this particular experiment. A 10% increase in the probability that the zero lower bound will bind in six quarters generates about a 10 basis point decline in 10-year forward inflation expectations. Under this conventional policy rule, the risk that the zero lower bound may bind in the future generates substantial downward pressure on longer-term inflation expectations.

In reality, researchers often document a sequential decline in longer-term real interest rates rather than the one-time shift we modeled in the previous experiment. Such a steady decline in real rates could have larger effects. Thus, to illustrate the full potential effect of the zero lower bound, we now simulate the model for a variety of different calibrations for β, drawing natural rate shocks randomly. For each β calibration, we simulate the economy 100,000 times and compute the probability that the economy hits the zero lower bound and the average level of inflation.[5] The blue line in Figure 2 plots the model-implied relationship between the probability of the binding zero lower bound and average inflation if the central bank only relies on its conventional policy rate alone to stabilize the economy.

Under this conventional policy rule, the presence of the zero lower bound can generate substantial downward pressure on longer-term inflation expectations. Moreover, Figure 2

[4] We set ϕ_π to a standard value of 1.5.

[5] Since households are rational and we solve the model using a global solution method (which takes account to probability of future shocks), average inflation and longer-term inflation expectations are equivalent in this framework.

highlights an important nonlinearity in the relationship between the binding zero lower bound and longer-term inflation expectations. The downward pressure on inflation expectations becomes *larger* as the zero lower bound binds more often. Intuitively, the decline in inflation expectations puts further downward pressure on policy rates which causes the zero lower bound to bind more often, further exaggerating the decline in inflation expectations. These results show that even a modest risk of a binding zero lower bound could cause policymakers to miss their longer-run inflation objective under a conventional policy rule.

2.3 Alternative: Stabilize the Economy Using Forward Guidance

However, policymakers can reduce the disinflationary effects of the zero lower bound if they consider policies that move beyond current interest rate policy alone. For example, suppose that instead policymakers chose to help stabilize the economy at the zero lower bound using expectations of future policy, commonly referred to as forward guidance. Building on Reifschneider and Williams (2000), the following history-dependent rule captures this idea:

$$i_t^d = r_t^n + \phi_\pi \pi_t - \phi_{id}\left(i_{t-1} - i_{t-1}^d\right). \tag{6}$$

Away from the zero lower bound (when policymakers are able to implement their desired policy rate), this policy rule generates identical outcomes to our previous conventional rule in Equation (5). However, once the economy hits the zero lower bound, policymakers commit to providing additional accommodation in the future to offset the higher-than-desired policy rates today. Although the zero lower bound constrains the central bank when the natural rate is negative, policymakers following this rule choose to keep interest rates at zero for some time after the natural rate becomes positive. Households and firms fully internalize these commitments to future policy accommodation which results in increased demand and higher prices in the face of the negative demand shock. If ϕ_{id} is set high enough, the economy can actually experience *above-target* inflation at the zero lower bound, a key feature of optimal policy under commitment.[6]

Thus, this simple rule captures the idea that policymakers can deliver outcomes similar to optimal policy under commitment at the zero lower bound using forward guidance about future policy. If policymakers intensively use forward guidance to stabilize the economy, then we no longer observe an erosion of longer-term inflation expectations due to the presence of the lower bound. The dashed red lines in Figure 1 highlights this idea using a calibration of

[6] Eggertsson and Woodford (2003) show that optimal policy under commitment at the zero lower bound implies a positive drift in the price level when the economy hits the zero lower bound.

$\phi_{id} = 1$ which implies policymakers fully offset the higher-than-desired rates today with lower rates in the future. Despite an increase in the probability that the economy will encounter the zero lower bound in the future, longer-term inflation expectations remain unchanged if policymakers choose to stabilize the economy using forward guidance.

Beyond that particular experiment, simulating a sequential decline in real rates in Figure 2 shows a linear and virtually flat relationship between the probability of a binding zero lower bound and longer-term inflation expectations. Because the economy no longer experiences bouts of below-target inflation at the zero lower bound, the red dashed line in Figure 2 shows that longer-term inflation expectations remain essentially unchanged even as the zero lower bound binds more often. These results highlight that the degree to which the zero lower bound weighs on inflation expectations crucially depends on the conduct of monetary policy.

2.4 A Second Alternative: Stabilize Using Asset Purchases

Instead of using forward guidance about future policy, policymakers can also reduce the disinflationary effects of the zero lower bound using large-scale asset purchases. To demonstrate this idea, we assume that policymakers follow the conventional policy rule in Equation (5) away from the zero lower bound but then engage in asset purchases once the short-term interest rate reaches the zero lower bound:

$$i_t^d = r_t^n + \phi_\pi \pi_t, \tag{7}$$

$$qe_t = \phi_{qe}\Big(i_t - i_t^d \Big). \tag{8}$$

The green dashed and dotted line in Figure 2 plots the model-implied relationship between average inflation and the probability of the binding constraint under this asset purchase rule. These results show that the central bank can also prevent the erosion of longer-run inflation expectations by engaging in asset purchases once policymakers' conventional tool becomes constrained.[7] Echoing our previous discussion, these results further highlight that

[7]For illustrative purposes, we set $\phi_{qe} = 1500$ in Figure 2. Equations (1) and (2) show that asset purchases have an expansionary effect on the output gap but have an offsetting disinflationary effect on inflation through a marginal cost channel in the Sims, Wu and Zhang (2023) model. As those authors discuss, this result implies that asset purchases are an imperfect substitute for conventional policy in response to natural rate shocks. As a result, policymakers must stimulate the output gap significantly at the zero lower bound (through a large ϕ_{qe}) to offset both the disinflationary channel of QE and natural rate dynamics through asset purchases. Recent work by Wu, Xie and Zhang (2024) argues that this disinflationary channel is important for understanding the contribution of unconventional monetary policy to the COVID inflation surge. While our results can't speak to the effects away from the zero lower bound, their results might imply

the degree to which the zero lower bound weighs on inflation expectations crucially depends on the conduct of monetary policy.[8]

2.5 Robustness of Results to Alternative Calibrations

We now illustrate how some of the model-implied relationships change under alternative calibrations. In Figure 3, we repeat our previous exercise using the conventional-only policy rule in Equation 5 under alternative calibrations and assumptions for the baseline model. Lowering the intertemporal elasticity of substitution (increasing σ from 1 to 2) or steepening the Phillips curve (raising κ from 0.03 to 0.1) does not materially affect the model's predictions. However, Figure 3 highlights that the assumptions on the stochastic shock process can affect the exact quantitative effect on longer-term inflation expectations. If we change from iid to persistent shocks (with an AR(1) coefficient equal to 0.75), Figure 3 shows a much larger decline in inflation expectations from a increase in the probability that the zero lower bound will bind in the future. Intuitively, persistent shocks imply longer-duration zero lower bound episodes which would have a larger negative effect on inflation expectations. In contrast, if we dramatically reduce the iid shock volatility in our baseline model (reduce σ^r by 50%), then we see a smaller quantitative effect.[9] This quantitative dependence on the shock process highlights why we want to discipline the natural rate process in our model using the natural rate estimates of Cúrdia et al. (2015). Moreover, it highlights that the model predictions under conventional only policy could be a lower bound as the Cúrdia et al. (2015) natural rate process is highly persistent, while we assume iid shocks in our baseline model.[10]

2.6 Empirically Testable Predictions

The findings in Figure 2 provide a key testable prediction regarding expectations of policymaker behavior at the zero lower bound. If households and firms in the economy believe that

that, under different calibrations, the disinflationary effects of LSAPs could be even stronger. Under those calibrations in which QE would be less effective, our results would suggest that forward guidance has been more important in offsetting the disinflationary effects of the zero lower bound.

[8] Wu, Xie and Zhang (2024) shows that tax-financed transfers could also be used as a stabilizing tool at the zero lower bound. While we think these policies might be quite important during the response to the recent COVID-induced recession, they are likely less salient during our pre-2020 period of analysis.

[9] To get additional variation in the probability that the zero lower bound will bind under this calibration, we have to solve the model with higher values for β.

[10] The results for the forward guidance or asset purchase rules are nearly unchanged given monetary policy's ability to stabilize the economy at the zero lower bound. So, we only conduct these robustness exercises using the conventional policy rule.

policymakers will effectively stabilize the economy at the zero lower bound using forward guidance, asset purchases, or some combination of the two, then we should see very little or no decline in longer-term inflation expectations in response to an increase of a binding zero lower bound. In contrast, if policymakers simply rely on conventional interest rate policy alone, then longer-term inflation expectations are adversely (and significantly) affected by an increase in the probability of encountering the lower bound.

We can translate these predictions into empirically-testable regression hypotheses using the model simulations from Figure 2. Specifically, we compute the implications of an increase in the probability of a binding zero lower bound on longer-term inflation expectations under each of the three policy specifications using the following regression:

$$\Delta\pi_{\beta}^{e,40} = b_0 + b^m \, \Delta p_{\beta}^{ZLB,6} + \varepsilon_{\beta}. \tag{9}$$

The right-hand side variable ($\Delta p_{\beta}^{ZLB,6}$) is the change in the 6-quarter ahead probability that the zero lower bound binds as β increases. The left-hand side variable is the model-implied change in the 10-year (40-quarter) forward inflation expectations as we increase β.[11] At a high level, this regression captures the average model-implied slope in Figure 2 under each policy. A large, negative b^m coefficient suggests a significant disinflationary effect of a potentially binding zero lower bound constraint. The first, third, and fifth columns in Table 1 contain the regression results under each of the three policy specifications.

If policymakers choose to only rely on their conventional policy rate at the zero lower bound, we find a precisely estimated coefficient of $\hat{b^m} = -1.32$, which implies nearly a 13 basis point decline in average expected inflation from a 10% increase in the probability of a binding zero lower bound. In contrast, under our assumed forward guidance or asset purchase rules, we find precisely estimated coefficients of b^m close to zero. These results suggest that, if we can isolate variation in the probability of the zero lower bound that is unrelated to the cyclical state of the economy, then we can use data on longer-term inflation expectations to infer perceptions of monetary policy behavior at the zero lower bound.

In addition, the results in Figure 2 highlight a second testable prediction. Under a conventional policy rule, Figure 2 shows that the slope of the curve becomes more negative as the probability of hitting the zero lower bound increases, implying a nonlinear relationship between the presence of the zero lower bound and inflation expectations. Intuitively,

[11] In our global solution method, we solve the model over a grid of β values, so the number of observations in each regression corresponds to the number of β grid points minus one since we take the difference with respect to β.

adverse feedback effects can arise whereby lower inflation expectations increase the odds the zero lower bound will bind, amplifying the initial decline in inflation expectations. We can formally model this potential relationship by adding a squared term to our previous regression:

$$\Delta\pi^{e,40} = b_0 + b_1^m \, \Delta p_\beta^{ZLB,6} + b_2^m \left(\Delta p_\beta^{ZLB,6}\right)^2 + \varepsilon_\beta. \tag{10}$$

The second, fourth, and sixth columns of Table 1 show the model-implied results of this nonlinear specification under each policy specification. We find evidence of a large and statistically-significant nonlinearity under a conventional policy rule. However, this nonlinear effect vanishes under either the forward guidance or asset purchase policies. Thus, the presence, or lack thereof, a nonlinearity in the relationship between the zero lower bound and longer-term inflation expectations can also help reveal the conduct of monetary policy at the zero lower bound. In the following section, we use financial market data to estimate these same regressions and attempt to uncover investors' perceptions about U.S. monetary policy in the presence of the zero lower bound.

3 Empirical Strategy

Our theoretical model illustrates a direct link between the probability that the zero lower bound binds and long-term inflation expectations. However, as we have shown, the strength of this disinflationary effect depends importantly on the conduct of monetary policy. Therefore, the extent to which the zero lower bound has weighed on inflation expectations in the United States must be estimated empirically. For our estimation, we employ high-frequency data on interest rate options and Treasury yields. Interest rate options are used to provide a measure of the probability investors are placing on the FOMC's policy rate reaching the zero lower bound in the future. In addition, spreads between nominal and inflation-indexed government debt provides investors' implied pricing of future inflation outcomes. We combine both data measures at a daily frequency and attempt to infer the causal link between the likelihood that the zero lower bound binds in the future and inflation expectations. Across a number of empirical specifications, we estimate modest disinflationary effects from the zero lower bound. Our estimates imply that, on average, the prospect of hitting the zero lower bound lowered long-term inflation expectations in the U.S. by just 10 basis points following the Global Financial Crisis.

3.1 Measuring the Probability of a Binding Zero Lower Bound

The Chicago Mercantile Exchange (CME) has offered options on interest rate futures since 1989. These options have since become the most actively traded exchange-listed interest rate options in the world. CME interest rate options are offered at various horizons (up to 10-years) and at various strike prices. The strike price defines the interest-rate level at which the options contract can be exercised, meaning once the interest rate futures price crosses that strike then the investor has the right to either purchase or sell an interest rate future at the strike price. Therefore, these options contracts allow investors to take positions to guard against future interest rate scenarios. Under the assumption that investors are risk-neutral, the price of those options contracts reflects the relative probability financial market participants assign to various interest rate events. Therefore, at a given future horizon, we can construct a probability distribution function (PDF) of future interest rates by examining prices of all traded interest-rate options at a given horizon.

We use daily data purchased directly from CME to construct the market-implied PDF for Eurodollar futures from 2008-2019.[12] We study the market-implied PDF at the 6-quarter-ahead horizon which is a short-enough horizon to ensure a sufficiently liquid market but is also far enough in the future to show variation during the period when the federal funds rate was pegged at the zero lower bound (2008-2015). The method we use to construct interest-rate PDFs follows Swanson (2006). This method discretizes future interest rate outcomes in bins centered at the strike price of traded options, then it solves for the best-fitting set of non-negative probabilities that rationalizes the prices of these options with their payoffs.[13] Intuitively, for two options with comparable payoffs, the algorithm assigns a higher probability to the options contract with a higher relative price. Finally, once a PDF is fitted to the options data, we can compute the probability that interest rates remain low, meaning at or very near the zero lower bound, in the future. To operationalize this method, we define a federal funds rate constrained at the zero lower bound as a Eurodollar futures rate at or below 50 basis points.[14]

[12] Over our sample, Eurodollar futures settled based on the 3-month USD LIBOR rate. However, since 2023, the Eurodollar futures market has closed and newer-issued options settle based on the Secured Overnight Financing Rate (SOFR).

[13] The payoff of an options contract is the price of the current interest rate future relative to the strike prices at which the options contract can be exercised. A contract that is "in-the-money" has a positive payoff whereas an "out-of-the-money" contract has a zero payoff at the current interest-rate futures price. This method for fitting the PDF uses data on all strikes regardless of whether they are in- or out-of-the-money.

[14] The LIBOR rate is highly correlated with the federal funds rate but there was historically a level difference between the two rates with the 3-month USD LIBOR rate roughly 30 basis points higher than

Figure 5 shows the time-series of the market-implied probability that the funds rate is at the zero lower bound 6-quarters in the future. The contours of this time series align well with zero lower bound encounters. In 2003, against a backdrop of falling inflation, the FOMC had set the target federal funds rate to 1 percent, an all-time low at the time. The risk of deflation had become elevated and led some to fear that rates may need to fall further. During this time, the probability that the funds rate would be at the zero lower bound in the future spiked to 25 percent. Then, as rates increased, the zero lower bound probability receded back to zero.

In 2008, the fallout from the Global Financial Crisis led the zero lower bound probability to increase again. In March 2008, following the near-failure of Bear Stearns, the probability that the funds rate would be at the lower bound 6-quarters in the future reached 30 percent. But later that year, even as the target federal funds rate declined and reached the zero lower bound, the probability that the funds rate would still be near zero 6-quarters ahead fell below 20 percent, suggesting that markets expected the stay at the zero lower bound would be short-lived. Figure 5 reveals that although the funds rate remained at the lower bound for seven years, expectations that an exit from zero rates was right around the corner were pervasive throughout the 2008-2015 period. In fact, the probability that the funds rate would be at the lower bound 6-quarters ahead never exceeded 90 percent throughout this period. We leverage this considerable variation in the market-implied zero lower bound probability, including throughout the 2008-2015 period, to identify the empirical relationship between longer-run inflation expectations and the likelihood that the zero lower bound binds in the future.

3.2 Estimating the Effect of the Zero Lower Bound on Inflation Expectations

Figure 5 demonstrates that the zero lower bound probability is partly driven by the Federal Reserve's own actions and announcements. Fed announcements that reduce rate expectations, all else equal, increase the likelihood that rates will be at zero in the future. For

the federal funds rate. Therefore, a 50 basis point Eurodollar futures rate would likely imply that the target range for the federal funds rate is between 0.00 and 0.25 percent which is the lowest target range set by the FOMC. During the GFC, the spread between LIBOR and other measures of the expected funds rate (such as OIS rates) widened, reflecting increases in credit risk for interbank loans. We address concerns arising from this period in our robustness analysis.

example, the probability that the funds rate would be at the lower bound 6-quarters ahead peaks at 88 percent following the August 9, 2011 FOMC meeting. The post-meeting statement on August 9, 2011 announced that the federal funds rate was likely to remain near zero "at least through mid-2013." This explicit language marked the FOMC's first use of date-based forward guidance and resulted in a large reduction in the expected path of the funds rate; hence investors grew more confident that the funds rate would still be at zero 6-quarters ahead (around February 2013). Assuming this use of forward guidance had its intended effect, it could conceivably stimulate economic activity and increase inflation expectations. Therefore, on FOMC meeting days like August 9, 2011, comovements between the zero lower bound probability and inflation expectations are not informative of the disinflationary effects that the zero lower bound might exert on longer-term inflation expectations.

A related concern could arise around inflation data releases. If inflation expectations are less than perfectly anchored, an unexpectedly weak CPI inflation release could simultaneously lower longer-term inflation expectations and expectations for the policy path in the coming quarters.[15] Again, in this instance, the correlation between longer-term inflation expectations and zero lower bound risks would not reflect the causal effects that the zero lower bound exerts on inflation expectations.

More generally, when using daily data, a variety of transitory factors can influence the 6-quarter ahead probability but may have little bearing on longer-term inflation expectations. This is shown in Figure 4 which simulates a negative natural rate shock and a permanent increase in β.[16] While both increase the 6-quarter ahead zero lower bound probability, only the latter spills over to both short-term and long-term inflation expectations.

These considerations highlight some potential pitfalls with studying the raw zero lower bound probability. We therefore follow a two step procedure to identify the causal link between the probability that policymakers are constrained by the zero lower bound in the future and longer-run inflation expectations. First, we regress the one-day change in the 6-quarter ahead market-implied probability of the zero lower bound binding on measures of FOMC policy surprises and the surprise component of key macroeconomic data releases. We rely on Swanson's (2021) measures of FOMC policy surprises which include surprise changes in the target federal funds rate, surprise changes in the FOMC's forward guidance,

[15]Bundick and Smith (2025) show that prior to 2012, market-based measures of longer-term inflation expectations drifted with CPI inflation surprises in the United States.

[16]For illustrative purposes, we assume natural rate shocks are persistent in this simulation.

and surprise changes in the FOMC's asset purchases.[17] For measures of macroeconomic data surprises, we use data from MMS to measure the difference between the actual release value and the expected release value.[18] Equation (11) formalizes our first-stage regression model:

$$\Delta p_t^{ZLB,6} = a_0 + a\, X_t^{surprises} + \varepsilon_t^{ZLB,6}, \tag{11}$$

where $\Delta p_t^{ZLB,6}$ denotes the one-day change in the market-implied probability on day t that the zero lower bound will bind 6-quarters in the future and $X_t^{surprises}$ denotes the vector of economic surprises comprised of both FOMC policy surprises as well as macroeconomic data surprises. The components of $X_t^{surprises}$ take a value of zero on days without an FOMC meeting or a particular data release. Given the relative infrequency of economic news releases (monthly or quarterly), the array of independent variables is sparse, which can cause standard corrections for heteroskedasticity to be biased downwards (Chesher and Jewitt, 1987). Therefore, throughout the paper we report bootstrapped standard errors using 10,000 replications of a moving-block bootstrap design with a block size of 60 business days.

Table 2 reports the results of the first-stage regression shown in Equation (11). Economic surprises have the expected effect on the zero lower bound probability. Better-than-expected data releases reduce the probability that the federal funds rate will be at the zero lower bound 6-quarters in the future, significantly so for initial jobless claims, capacity utilization, non-farm payrolls, and retail sales data. These may be interpreted through the lens of the theoretical model as natural rate shocks that drive cyclical fluctuations in the economy, but may have little bearing on longer-term inflation expectations. FOMC forward guidance communication and asset purchase announcements can also significantly affect the probability that the funds rate is at the zero lower bound in the future. Forward guidance indicating that rates will be lower in the future increases the probability that the funds rate will be at the zero lower bound 6-quarters ahead. And perhaps reflective of signaling effects, a surprise increase in asset purchases also increases the probability that the funds rate will be at the zero lower bound 6-quarters in the future. These are precisely the variations in the zero lower bound probability that we aim to control for with this first-stage regression.

We next regress the one-day change in market-implied measures of longer-term inflation expectations on the residuals from this first-stage regression. Our focus on long-term

[17] Swanson's (2021) policy shocks series ends in 2019, so we choose the end point of our sample at that time to ensure we have consistent controls throughout our analysis.

[18] We standardize the macroeconomic data surprises so that the surprises are mean zero and are scaled to have a unit standard deviation. These data were obtained from Haver Analytics.

inflation expectations is guided by our theoretical model. Figure 4 shows that short-term inflation expectations respond to transitory natural rate shocks. To the extent that our first-stage regression can't perfectly control for these fluctuations, the correlation between the zero lower bound probability and near-term inflation expectations might reflect typical business cycle patterns in interest rates and inflation. Our baseline regression therefore uses the instantaneous 10-year forward inflation breakeven which reflects the market-implied expectation of what annualized CPI inflation will be 10-years in the future. Equation (12) formalizes our second-stage regression model:

$$\Delta\pi_t^{e,40} = b_0 + b\,\hat{\varepsilon}_t^{ZLB,6} + \varepsilon_t^{\pi,40}, \tag{12}$$

where $\Delta\pi_t^{e,40}$ denotes the one-day change in the market-implied inflation expectation on day t for inflation 10-years (40 quarters) forward and $\hat{\varepsilon}_t^{ZLB,6}$ denotes the estimated residuals from the first-stage regression. The estimated coefficient on the the zero lower bound probability — b — is the key parameter of interest. We interpret b as the elasticity of longer-term inflation expectations with respect to the probability that the federal funds rate is constrained by the zero lower bound in the future.

Table 3 reports the estimates of the regression model shown in Equation (12). The coefficient b is estimated to be $\hat{b} = -0.29$, implying that a 10 percentage point increase in the likelihood that the zero lower bound will bind in the future reduces longer-term inflation expectations by about 3 basis points. The negative sign is consistent with predictions from our theoretical model presented in Section 2. However, the small magnitude suggests the disinflationary effects of the zero lower bound are relatively modest. Interestingly, despite its conceptual appeal, we find that the first-stage regression has virtually no effect on the estimate of b. For example, if we estimate equation (12) with the one day change in the raw zero lower bound probability in place of the residualized probability, the coefficient b is still estimated to be $\hat{b} = -0.29$.[19]

To map the coefficient estimates of b into a cumulative, or level, effect on inflation, we calculate that the average probability that the zero lower bound will bind 6-quarters in the future over our sample is roughly 31%. Therefore, we estimate that the specter that the funds rate will be constrained by the zero lower bound has only reduced inflation expecta-

[19]The similarity of the two estimates suggests that the relationship between inflation expectations and the probability of being constrained at the zero lower bound in the future is not driven by variation around macroeconomic data releases or FOMC announcements and may instead reflect secular forces, fiscal policy, or international determinants.

tions in the United States by about 10 basis points, on average since 2008 (computed by $31\% \times -0.29$) . Figure 6 plots the estimated relationship between the zero lower bound and longer-term inflation expectations along with the uncertainty around our estimate. Compared to the much larger disinflationary effects that arise under conventional monetary policy rules in Section 2, our estimates suggest that the FOMC's use of unconventional policy tools may have played an important part in mitigating the potentially deleterious effects that the zero lower bound can have on inflation expectations. Before formally investigation this through the lens of our theoretical model, we first review some relevant sensitivity analysis on these empirical estimates.

We begin our sensitivity analysis by noting that oil prices are highly correlated with the market-based measures of inflation expectations we study, even at long horizons. While Elliot et al. (2015) has suggested that this correlation may result from the zero lower bound on interest rates, other channels such as risk-premia driven by common macro factors could be at play as well (Perez-Segura and Vigfusson, 2016; Hammoudeh and Reboredo, 2018). This latter possibility raises the question of whether the estimated relationship between the zero lower bound probability and inflation expectations is biased by omitting changes in oil prices. Table 3 shows that, as expected, the coefficient on the one-day percent change in WTI prices is positive and statistically significant. However, controlling for the one-day percent change in WTI prices reduces — but does not eliminate — the negative relationship between the zero lower bound and longer-term inflation expectations. Importantly, the 90% confidence interval for b when controlling for WTI price changes spans (-0.33, -0.15) and therefore includes the point estimate of b from our baseline regression.

The next variation of our baseline regression explores whether the probability that the zero lower bound binds in the future exerts a nonlinear effect on inflation expectations. In our theoretical model, adverse feedback effects can arise whereby lower inflation expectations increase the odds the zero lower bound will bind, amplifying the initial decline in inflation expectations. Interestingly, when we introduce the squared (residualized) zero lower bound probability into the regression model, nonlinear effects are found to be negative and statistically significant. This was our second testable implication from Section 2. However, the point estimate is small in magnitude compared to the very large, negative coefficients found in Table 1 of Section 2 under conventional policy. Moreover, the next column in Table 3 shows that the statistical significance of these nonlinear effects vanishes once we control for the one-day percent change in WTI prices.

Next we explore the robustness of these regression results to outliers. With daily financial data that spans the GFC, a period during which markets were extremely strained at times, there is a high likelihood that our sample includes extreme observations that could have an outsized influence on our regression estimates. To guard against this, we estimate the previously discussed regression models using the least absolute deviation (LAD) objective function rather than the sum of squared residuals minimized by ordinary least squares (OLS). The LAD results are shown in the far right panel of Table 3. The LAD estimates confirm that a higher probability that the zero lower bound will bind has exerted only a modest negative drag on longer-term inflation expectations in the U.S. This effect remains statistically significant when accounting for fluctuations in oil prices. Unlike the ordinary least squares estimates, the LAD estimates reveal no indication of nonlinearities in the transmission from zero lower bound risk to inflation expectations, regardless of whether or not we control for changes in oil prices. Upon further investigation, we found that the statistical significance of nonlinear zero lower bound effects on inflation expectations from the OLS regression hinges on a single observation (March 9, 2009); confirming the results from the more robust LAD estimates.

Another question concerns whether we should estimate our regression model in levels or first differences. Our baseline approach is to estimate the regression model in first differences to avoid potentially spurious correlations in the data. From the viewpoint of our theoretical model, estimating the model in levels versus differences should not matter. If inflation expectations exhibit a unit root solely because of a permanently higher zero lower bound probability, then a regression in levels would capture this cointegration. In the data, if other shocks have a permanent effect on forward inflation compensation, then longer-term inflation compensation may have trends which are unrelated to the zero lower bound probability, potentially leading to spurious estimates in a levels regression.[20] Instead of taking a strong stand on levels versus differences, for robustness, we estimate a bi-variate VAR in levels with our daily measure of the probability that the zero lower bound will bind in the future ($p_t^{ZLB,6}$) and long-term forward inflation compensation ($\pi_t^{e,40}$). Sims, Stock and Watson (1990) helpfully show that impulse responses from a levels VAR are valid whether the variables are I(0), I(1) and not cointegrated, or I(1) and cointegrated. We then study the impact effect on $\pi_t^{e,40}$ to a one unit increase in $p_t^{ZLB,6}$. Reassuringly, this levels VAR-

[20]More formally, we can not statistically reject that inflation expectations in the data have a unit root. Nor can we reject that our empirical zero lower bound probability has a unit root. However, a Stock and Watson (1993) Dynamic OLS cointergration test does not reveal any long-run relationship between the two I(1) series. However, pre-testing is not definitive because unit-root tests tend to have low power.

based estimate is -0.30 (with a standard error of 0.04) which almost perfectly recovers our first-differences OLS estimate.

Our final sensitivity analysis explores how our regression estimates change over different sub-samples. One concern with our baseline sample of Dec-2008 through Jun-2019 is that it includes periods of severe interbank funding stress during the GFC. In late 2008 and early 2009, LIBOR rates spiked well above overnight-indexed swaps of comparable maturities, reflecting credit risk in the interbank market. These strains caused LIBOR rates to become disconnected from policy rate expectations. If Eurodollar investors expected this spike in LIBOR rates to persist into the future, it could bias down our measure of zero lower bound risk and lead us to overstate the effects of the zero lower bound on inflation expectations.[21] We address this concern by dropping the precipice of the GFC from our sample and estimating our regression from July 2009 through December 2019. The coefficient estimates are shown alongside our baseline estimates in Table 4. The post-GFC sample point estimates are little changed from our baseline estimates and still statistically significant.[22]

The third column of Table 4 shows the estimated coefficients over the Pre-ZLB sample. This earlier sample omits the GFC and therefore is another way to avoid the period with elevated LIBOR rates. This sample is also interesting because it pre-dates the use of LSAP and more explicit forward guidance policies. Consistent with our interpretation that these policies have been important in blunting the disinflationary effects of the zero lower bound on longer term inflation expectations, we find larger (in magnitude) coefficients in the pre-ZLB sample. For instance, when controlling for oil prices, the point estimates are roughly doubled. However, our estimates over this pre-ZLB period are also less precise, as variation in the zero lower bound probability was more muted (as can be seen in Figure 5).

We conclude from our empirical analysis that the risk of hitting the zero lower bound has imparted a small, albeit statistically significant, reduction in longer-term inflation expectations. In the next section, we bring these empirical results to our theoretical model to

[21] Mechanically, higher LIBOR rates would imply a lower likelihood that Eurodollar rates settle below 50 basis points, therefore reducing our measure of the probability of being at the zero lower bound in the future. If the rise in in expected LIBOR rates reflects expectations of funding stress rather than policy rate expectations, this reduced likelihood would be misleading in the sense that it doesn't actually reflect expectations for higher policy rates.

[22] In addition, if we end our estimation sample in 2015 (when the policy rate lifts off of the zero lower bound), we find a coefficient of -0.28 (standard error of 0.06), which is very close to our baseline estimate of -0.29 (standard error of 0.06).

better understand how actual FOMC policy has been conducted in the presence of the zero lower bound.

4 Policies Consistent with Our Empirical Estimates

Our theoretical model frames a range of inflation outcomes in the presence of the zero lower bound. Policymakers who rely solely on conventional monetary policy allow inflation expectations to fall well-below target in the presence of the zero lower bound. Alternatively, policymakers who employ forward guidance or large-scale asset purchases can largely eliminate reductions in inflation expectations in the presence of the zero lower bound. These outcomes are consistent with the previous literature which has argued that policymakers who can commit to future interest-rate policies or are willing to use large-scale asset purchases can deliver near-optimal policy outcomes despite the zero lower bound. We formalized these alternatives with two testable hypothesis stemming from regressions of inflation expectations on the probability that the zero lower bound will bind.

Informed by our empirical regression, we now return to the model-based regressions to infer where FOMC policy lies on the range of policy outcomes described above; severe disinflation vs. near-optimal policy. For this reason, we frame this exercise as answering the question: How optimal was U.S. monetary policy at the zero lower bound? Our answer to this question not only reveals the extent to which these policies were used but also whether they were effective in promoting price stability. This is important because although the narrative account shows considerable use of unconventional monetary policy, there is a good deal of debate over whether forward guidance and asset purchases are all that effective (Del Negro, Giannoni and Patterson, 2023; Greenlaw et al., 2018)

Our evaluation of policy seeks to align the model-implied regressions with their empirical counterparts. To do this, we fix non-policy parameters and then select key monetary policy reaction coefficients to minimize the distance between $\hat{b^m}$ and $\hat{b}$, where these coefficients are, respectively, model and data estimates of the sensitivity of longer-term inflation expectations to the probability that zero lower bound will bind.[23] We numerically search using guess and verify for the forward guidance parameter ϕ_{id} and the asset purchase parameter ϕ_{qe}. For each calibration, we solve our nonlinear model and select grid of β parameters which drives

[23]Specifically, b^m is estimated from the regression defined in Equation (9) and b is estimated from the regression defined in Equation (12). We choose to work with the linear regression specifications since we didn't find robust evidence of nonlinear effects in our empirical analysis.

variation in the probability that the zero lower bound binds. Then, for each choice of policy parameter, we estimate $\hat{b^m}$ by estimating the regression in Equation (9). We select the policy parameter which brings $\hat{b^m}$ closest to $\hat{b}$ for both the forward guidance and asset purchase policy rules.

Table 5 reveals our main finding: U.S. monetary policy performed well at the zero lower bound. We estimate that $\phi_{id} = 0.87$ can deliver the observed empirical relationship between longer-term inflation expectations and the probability that the zero lower bound will bind. This setting of $\phi_{id} = 0.87$ implies a substantial, albeit less-than-perfect offset of higher-than-desired policy rates at the zero lower bound through the use of forward guidance. Recall that $\phi_{id} = 1$ fully offset higher-than-desired rates at the zero lower bound and, from Section 2.3, delivers impulse responses consistent with optimal policy under commitment. Similarly, we find that the modest empirically estimated disinflation from the zero lower bound can be rationalized by an aggressive asset purchase rule. Setting $\phi_{qe} = 502$ results in a model-implied estimate of b^m of approximately -0.29, the same as the empirical moment being targeted. This setting of ϕ_{qe} implies that for every annualized percentage point wedge between the actual policy rate and the desired policy rate, the central bank increases the size of its balance sheet by roughly a factor of a 1.2 units of GDP. This may seem aggressive, however, in reality, FOMC policymakers used a mix of the two policies (forward guidance and asset purchases). This exercise reveals that each unconventional tool can, individually, account for the estimated empirical effects of the zero lower bound on longer-term inflation expectations.

Figure 6 shows the implications for these empirically calibrated policies for the level of inflation expectations. Compared to the severe deterioration in inflation expectations under conventional monetary policy shown in Figure 2, these empirically-calibrated forward guidance and asset purchase policy rules lead to only very modest declines in longer-term inflation expectations as the probability of the zero lower bound increases. Therefore, despite considerable debate about their effectiveness, our results suggest that the Federal Reserve's use of forward guidance and asset purchases played an instrumental role in keeping inflation expectations from slipping too low in the face of the zero lower bound.

4.1 If Tools Were Effective, Why Did Inflation Run Below Target?

Despite the effective use of forward guidance and asset purchases at the zero lower bound, inflation still ran below the FOMC's 2 percent objective throughout much of the 2012-2019 sample period. How can we reconcile our results with this outcome? This paper provides a detailed analysis into one possible explanation but, by itself, doesn't provide a complete answer. Instead, our results eliminate one possible explanation, arguing that low inflation expectations due to the presence of the zero lower bound was *not* the primary culprit for the below-target inflation in the 2010's.

However, it is also possible that inflation was pulled down by low inflation expectations for reasons other than the zero lower bound. For example, in Bundick and Smith (2021), we argue that communications from policymakers prior to the formal adoption of an inflation objective may have initially anchored inflation expectations below 2 percent. That work presents high-frequency evidence that the introduction of longer-run inflation projections in the Summary of Economic Projections in 2009, together with the formal adoption of the inflation target in 2012, helped better anchored inflation expectations. However, Chart 5 in that paper (reproduced as Figure 7 in this paper), shows that the views on longer-run inflation initially communicated by policymakers from the 2009-2012 SEP were centered below 2 percent. In that work, we argue that this policy communication may have anchored inflation expectations below 2 percent. It's clear from subsequent FOMC communications that policymakers were aware that their 2 percent target may have been perceived as a ceiling, as this was a rationale behind the introduction of the word "symmetric" in describing the 2 percent inflation objective in the revised January 2016 Statement on Longer-Run Goals and Objectives. Another possible explanation could be that a sequence of disinflationary shocks pushed inflation below target. In either case, the results in this paper suggests that factors aside from the presence of the zero lower bound likely explain persistently below-target inflation in the 2010's.

5 Conclusions

In recent years, several major central banks have taken steps to refine their approaches to inflation targeting. For example, the Federal Reserve and the European Central Bank completed comprehensive monetary policy strategy reviews in 2020 and 2021, respectively. These reviews were undertaken, in part, to address the increased risk of hitting the zero lower bound which could impede the attainment of price stability mandates by allowing inflation expectations to slip below target-consistent levels. The Federal Reserve went on to adopt a new average inflation targeting framework that seeks to explicitly keep inflation expectations from falling below target. However, in this paper we provide fresh evidence that even before the adoption of this new framework in 2020, the Federal Reserve's use of forward guidance and asset purchases greatly limited the erosion of longer-term inflation expectations arising from the zero lower bound constraint. Our results suggest that even in the presence of elevated zero lower bound risk, central banks can deliver near-optimal stabilization policies using forward guidance and asset purchases without needing to alter their inflation frameworks.

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Table 1: Testable Predictions Using Simulated Data Under Alternative Monetary Policies at the Zero Lower Bound

	Δ Long-Term Inflation Expectations					
	Conventional Policy		Forward Guidance		Asset Purchases	
$\Delta p_{\beta}^{ZLB,6}$	-1.32^{***}	-0.68^{***}	-0.01^{***}	-0.01^{***}	-0.04^{***}	-0.05^{*}
	(0.06)	(0.09)	(0.00)	(0.00)	(0.01)	(0.03)
$\left(\Delta p_{\beta}^{ZLB,6}\right)^2$		-19.17^{***}		0.12		0.17
		(2.57)		(0.16)		(0.35)
Obs	50	50	50	50	50	50

Each regression denotes the model-implied relationship between longer-run inflation expectations and the probability of a binding zero lower bound constraint under three alternative monetary policy at the zero lower bound: (1) Policymakers only rely on their conventional policy tool, (2) they choose to stabilize the economy with forward guidance about future policy, or (3) they engage in asset purchases at the zero lower bound. See Section 2.6 for additional details.

Note: OLS standard errors are shown in parenthesis. *, **, or *** implies that the p-value is less then 0.10, 0.05, or 0.01, respectively.

Table 2: Response of the Probability of the Zero Lower Bound to Macroeconomic Surprises

	Estimate	Std. Err.
Constant	−0.0001	0.0003
Macroeconomic Data Surprises		
Initial jobless claims	0.0027**	0.0012
Capacity utilization	−0.0020*	0.0016
New home sales	−0.0003	0.0015
CPI (core)	0.0006	0.0028
PPI (core)	0.0021	0.0027
Non-farm payrolls	−0.0173***	0.0030
Unemployment rate	0.0016	0.0022
Retail sales	−0.0043**	0.0018
Consumer confidence	−0.0003	0.0019
Leading indicators	−0.0038	0.0025
ISM Mfg.	−0.0036	0.0028
GDP (advance)	−0.0042	0.0035
Employment cost index	−0.0061	0.0049
FOMC Meeting Surprises		
Fed Funds	0.0079	0.0192
Forward Guidance	−0.0190***	0.0045
LSAP	0.0123***	0.0040

Number of observations: 2582. The sample period is December 16, 2008 – June 30, 2019.

Note: Standard errors are bootstrapped using 10,000 replications of a moving-block bootstrap design with a block size of 60 business days. *, **, or *** implies that the 90%, 95%, or 99% bootstrapped confidence interval excludes zero, respectively.

Table 3: Response of Long-Term Inflation Expectations to the Probability of the Zero Lower Bound

	Δ 10-yr Forward Inflation Expectations							
	OLS Estimates				LAD Estimates			
$\hat{\varepsilon}_t^{ZLB,6}$	-0.29^{***}	-0.23^{***}	-0.29^{***}	-0.23^{***}	-0.30^{***}	-0.24^{***}	-0.30^{***}	-0.24^{***}
	(0.06)	(0.06)	(0.06)	(0.05)	(0.06)	(0.06)	(0.06)	(0.05)
$\left(\hat{\varepsilon}_t^{ZLB,6}\right)^2$			-1.36^{*}	-1.12			-0.11	-0.43
			(0.86)	(0.92)			(0.74)	(0.72)
Δ log(WTI Oil)		0.33^{***}		0.33^{***}		0.27^{***}		0.27^{***}
		(0.07)		(0.06)		(0.05)		(0.06)
Obs	2583	2488	2583	2488	2583	2488	2583	2488

The sample period is December 16, 2008 – June 30, 2019.

Note: Standard errors are bootstrapped using 10,000 replications of a moving-block bootstrap design with a block size of 60 business days. *, **, or *** implies that the 90%, 95%, or 99% bootstrapped confidence interval excludes zero, respectively.

Table 4: Split Sample Responses of Long-Term Inflation Expectations to the Probability of the Zero Lower Bound

	Δ 10-yr Forward Inflation Expectations					
	Baseline Sample Dec 2008 - Jun 2019		Post-GFC Sample July 2009 - June 2019		Pre-ZLB Sample April 2002 - Dec 2008	
$\hat{\varepsilon}_t^{ZLB,6}$	-0.29^{***}	-0.23^{***}	-0.27^{***}	-0.21^{***}	-0.53^{*}	-0.49^{*}
	(0.06)	(0.06)	(0.05)	(0.05)	(0.32)	(0.30)
Δ log(WTI Oil)		0.33^{***}		0.34^{***}		0.06
		(0.07)		(0.07)		(0.11)
Obs	2583	2488	2448	2358	1634	1579

Note: Standard errors are bootstrapped using 10,000 replications of a moving-block bootstrap design with a block size of 60 business days. *, **, or *** implies that the 90%, 95%, or 99% bootstrapped confidence interval excludes zero, respectively.

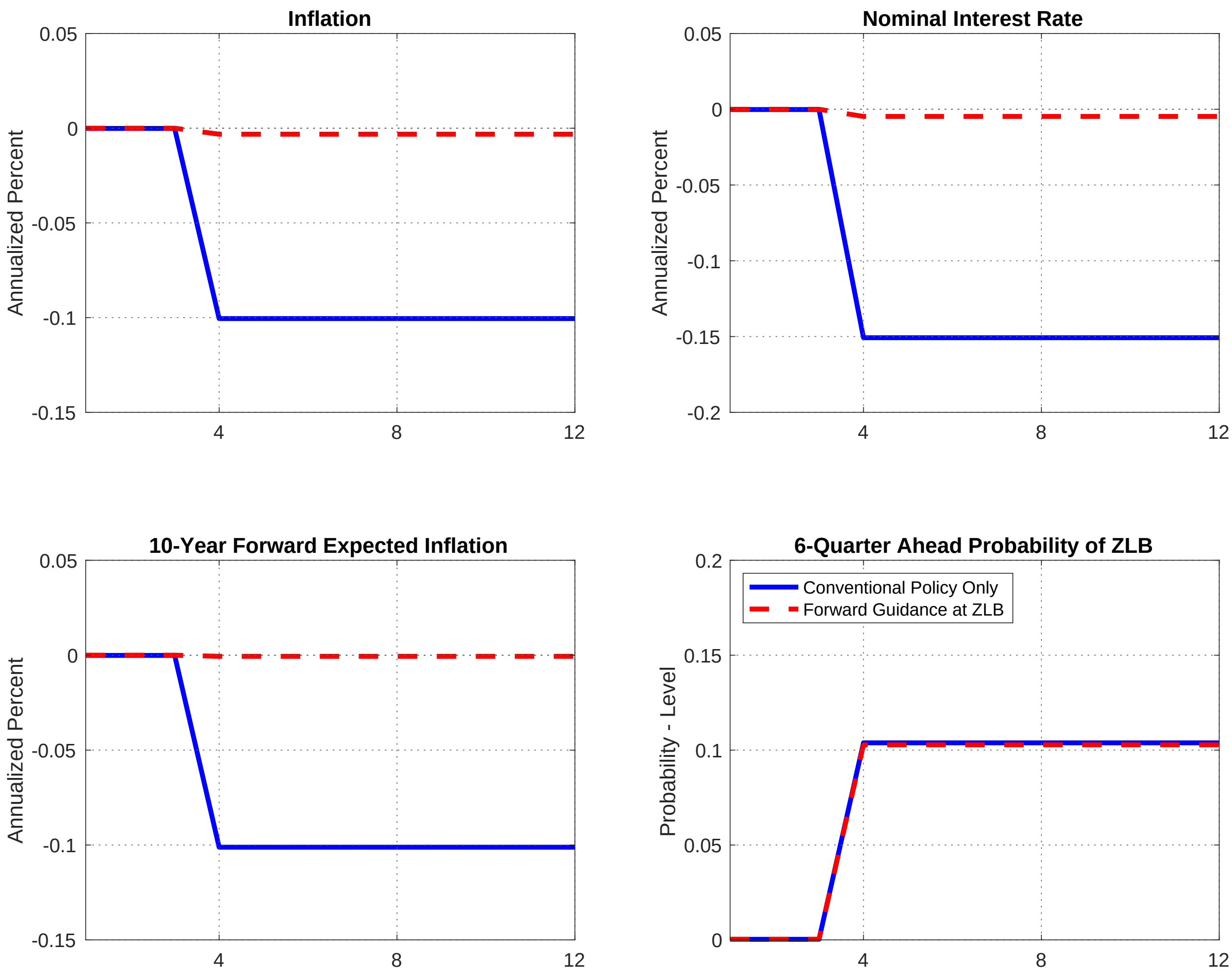
Table 5: Matching Empirical Evidence Using Alternative Policies in the Model

	Δ Long-Term Inflation Expectations		
	Data	**Model**	
	Target Moment	Forward Guidance	Asset Purchases
$\Delta p^{ZLB,6}$	-0.29^{***}	-0.30^{***}	-0.29^{***}
	(0.06)	(0.03)	(0.04)
Obs	2583	50	50

Data Note: See Section 3.2 for additional details. For the data moment, standard errors are bootstrapped using 10,000 replications of a moving-block bootstrap design with a block size of 60 business days. *** implies that the 99% bootstrapped confidence interval excludes zero.

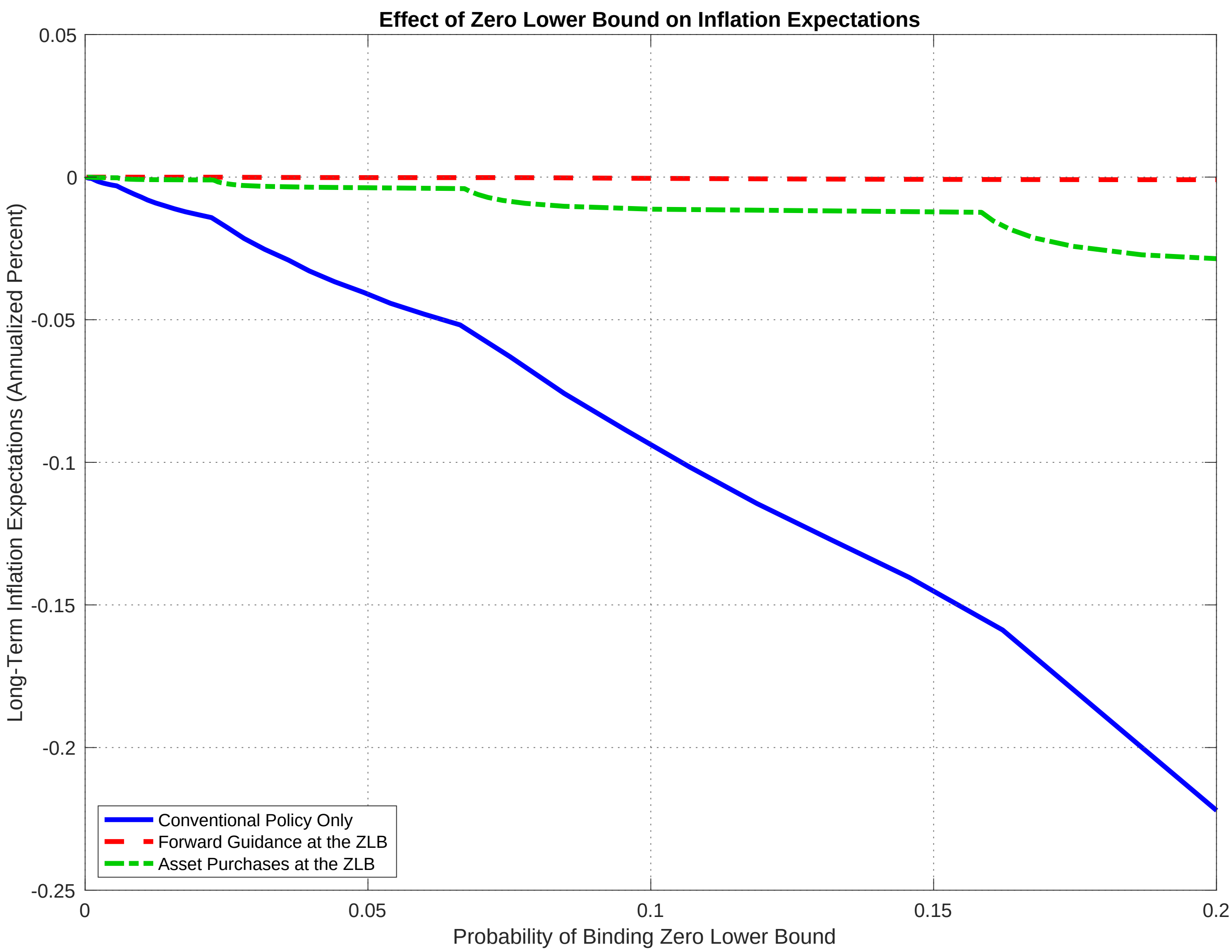
Model Note: See Section 4 for additional details. For the model moments, OLS standard errors are shown in parenthesis. *** implies that the p-value is less than 0.01.

Figure 1: Responses to Higher Probability that the Zero Lower Bound Will Bind in Future



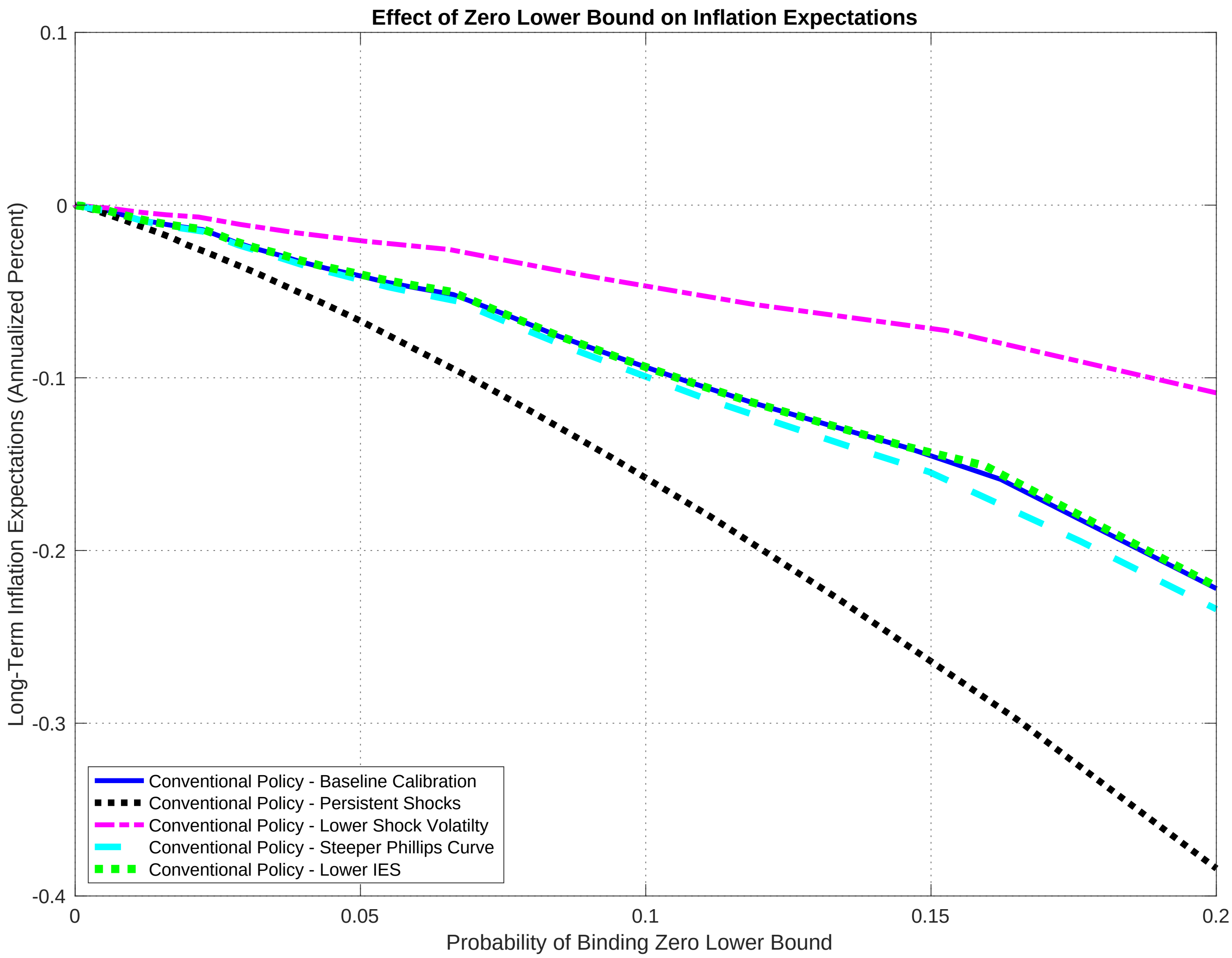
Note: Each line denotes the responses to a decline in longer-run real rates (an increase in β) under the assumption policymakers only rely on their conventional policy tool or if they choose to stabilize the economy with forward guidance about future policy. See Sections 2.2 or 2.3 for additional details.

Figure 2: Inflation Expectations and the Probability of a Binding Zero Lower Bound



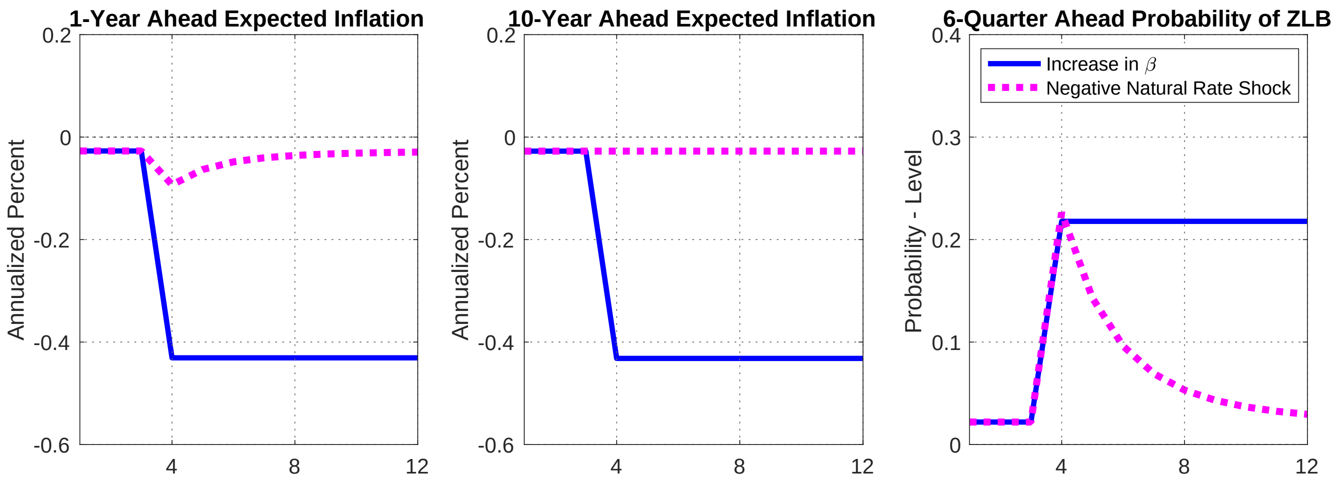
Note: Each line denotes the model-implied relationship between longer-run inflation expectations and the probability of a binding zero lower bound constraint under three alternative monetary policy at the zero lower bound: (1) Policymakers only rely on their conventional policy tool, (2) they choose to stabilize the economy with forward guidance about future policy, or (3) they engage in asset purchases at the zero lower bound. See Sections 2.2, 2.3, and 2.4 for additional details.

Figure 3: Alternative Calibrations Under Conventional Only Policy Rule



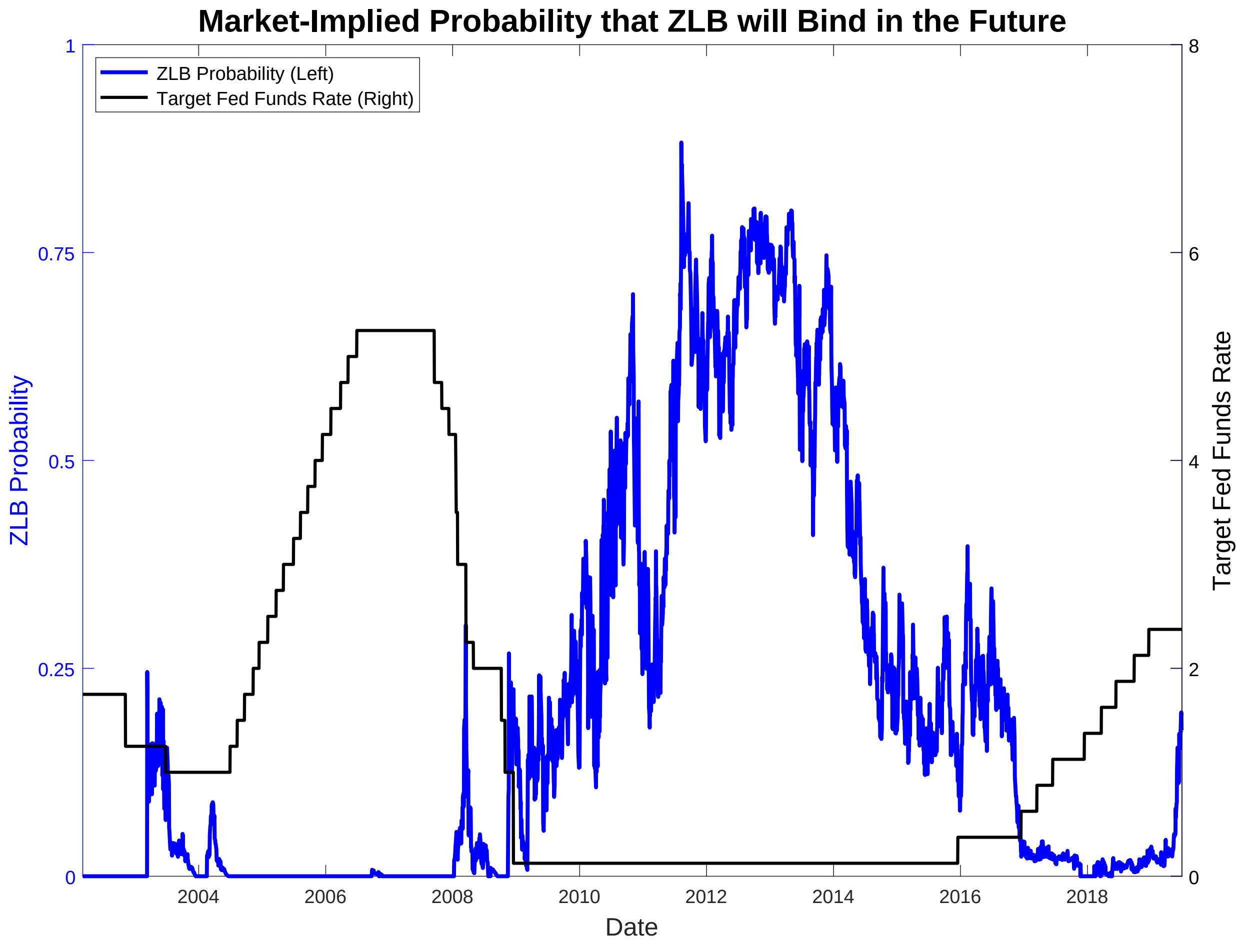
Note: Each line denotes the model-implied relationship between longer-run inflation expectations and the probability of a binding zero lower bound constraint under the assumption that policymakers only rely on their conventional policy tool for different calibrations of the model parameters. See Section 2.5 for additional details.

Figure 4: Outcomes Under Natural Rate Shock Versus Permanent Change in β



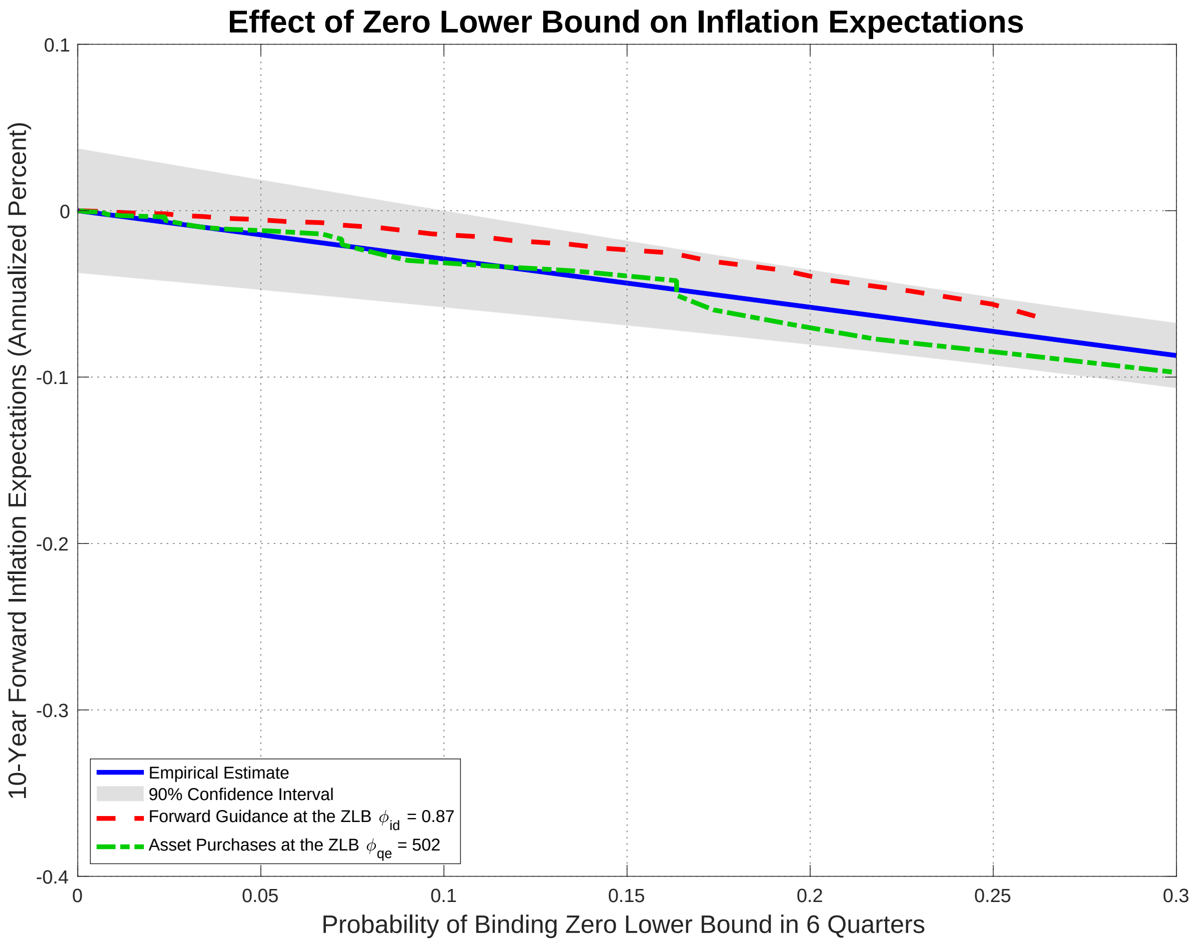
Note: These responses are produced under the assumption that policymakers only rely on their conventional policy tool. See Section 3.2 for additional details.

Figure 5: Zero Lower Bound Probability



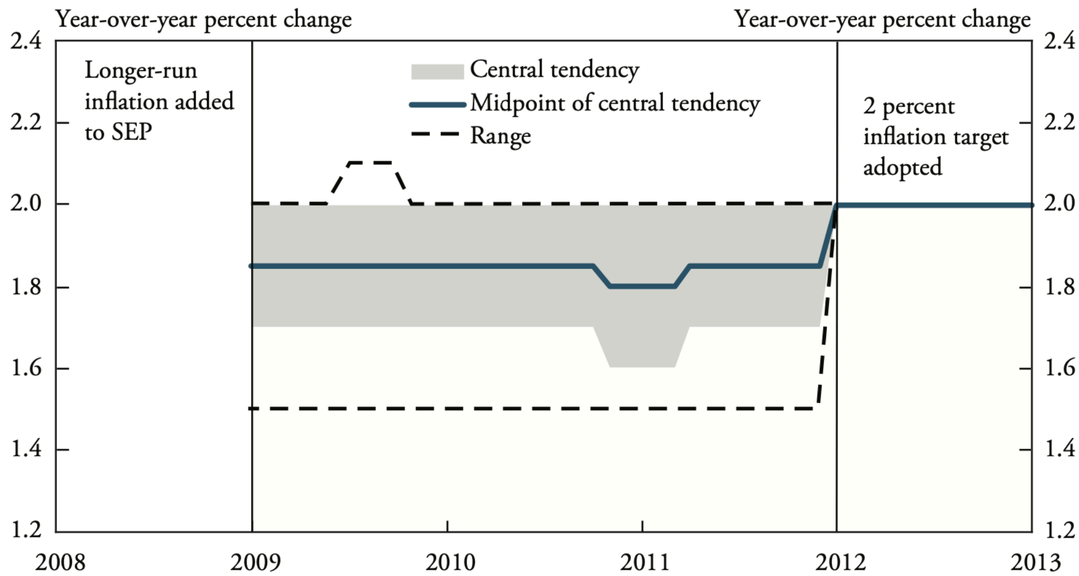
Note: The solid blue line shows the market-implied probability that the zero lower bound will bind 6-quarters in the future. The solid black line shows the FOMC's target federal funds rate.

Figure 6: Relationship Between Zero Lower Bound Probability and Inflation Expectations



Note: The solid blue line and gray shaded region denote the estimated empirical relationship between the probability that the zero lower bound will bind and inflation expectations. The prediction interval is constructed from the bootstrapped standard errors from the regression model shown in Equation (12).

Figure 7: FOMC Summary of Economic Projections for Longer-Run PCE Inflation



Notes: Longer-run projections represent each FOMC participant's assessment of the rate to which inflation would be expected to converge under appropriate monetary policy and in the absence of further shocks to the economy. The central tendency discards the three highest and three lowest projections.

Source: Chart 5 from Bundick and Smith (2021)