Interest Rate Rules, Forward Guidance Rules and the Zero Lower Bound on Nominal Interest Rates in a Cost Channel Economy

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Abstract

The main aim of this study is to examine the behaviour of main macroeconomic variables under some interest rate rules and a forward guidance rule in a cost channel economy[1] in the presence of the ZLB. The ZLB is considered as an occasionally binding constraint. Interest rate rules are represented by Taylor-type truncated rules (TTR) while the forward guidance (FG) rule is an endogenous threshold-based rule. Under TTRs, first, the cost channel economy is more likely to fall into a liquidity trap and remain longer compared to the no-cost channel economy. Second, *the risky steady state* of a cost channel economy has more deflation bias than a no-cost channel economy. Third, the welfare loss is higher when uncertainty is high and it is appreciably higher in cost channel economies. Under the FG rule, compared to the TTR, the following results hold, irrespective of the cost channel: First, an appropriate FG rule can avoid deflation bias while strict FG leads to *an inflation bias.* Second, the FG rule reduces the frequency of liquidity-trapped recessions. Third, the depth of the recession under the FG rule is lower. The existence of the cost channel amplifies the inflation bias under the FG rule.

The findings of this study suggest that if a cost channel was present in an economy, the transmission of monetary policy may be different from that in a no-cost channel economy in the presence of the ZLB. Additionally, if agents expect future recessions, achieving the inflation target is more

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[1]A cost channel is said to be present in an economy if changes in nominal interest rates affect the supply-side of the economy.

challenging in cost channel economies. Therefore, central banks should pay careful attention to the cost channel of monetary policy when they set policies under such economic conditions. Further, this study finds that the endogenous FG rule improves welfare compared to the interest rules considered.

Keywords: cost channel of monetary policy, zero rates on interest rates, interest rate rules, forward guidance rules, inflation bias, deflation bias

JEL Classification: E31, E32, E43, E52, E58

1 Introduction

Rules have generally been used to approximate central bank policies and predict them. It is well known that normal central banking activities, as well as economic activities, are affected by the existence of the zero lower bound on nominal interest rates (ZLB).[2] This is no different with regard to monetary policy rules.[3] Studies of monetary policy rules with occasionally binding ZLB constraint have shown that the ZLB not only aggravates recessions, but also affects deterministic steady state values. However, the impact of the supply-side effects of monetary policy on economic conditions under monetary policy rules at the ZLB has not been examined thus far. The main aim of the present study is to begin filling this gap in the literature by analysing interest rate rules at the ZLB when monetary policy has supply-side effects. This is important because the existence of the supply-side effects of monetary policy involves direct feedback effects on nominal interest rates and inflation through monetary policy rules, especially, interest rate rules.[4] This direct feedback mechanism of supply-side effects may affect previous results under monetary policy rules with the ZLB constraint. The supply-side effects of monetary policy is incorporated by considering the cost channel of monetary policy. This research also proposes an endogenous threshold-based forward guidance (FG) policy rule.[5] Ac-

[2]In this study, I consider the short-term nominal interest rate is constrained by the zero lower bound. However, on a few occasions, as specified in those sections, I relax that assumption.

[3]Monetary policy rules, in the context of this study, can be defined as follows: The central bank follows a monetary policy rule to set current nominal interest rates. The rule is directly expressed by economic variables such as the inflation rate, price level, output gap, lags and leads of those variables and nominal interest rates.

[4]For example, a negative demand shock contracts output and creates deflationary pressure. The central bank cuts nominal interest rates as prescribed by the interest rate rule. This expansionary monetary policy reduces the cost of production and thereby inflation through the cost channel mechanism and this feeds back to a larger interest rate cut in the next period, and so on.

[5]In general, forward guidance is considered as the central bank's public announcement of its near future policy plan. The literature identifies two major categories of forward guidance, namely, Odyssean and Delphic (see Campbell et al., 2012). In Odyssean forward guidance, the monetary authority publicly commits to a future action (for an application see Boneva et al., 2015). In Delphic forward guidance, the monetary authority merely forecasts and announces macroe-

cording to this FG rule, the central bank announces forward guidance well before a recession and activates the rule endogenously during a recession.

Monetary policy rules have been in discussion since Adam Smith.[6] For example, in the 18th century, in the UK, a rule called *the real bills doctrine* was proposed for liquidity expansion. Under this rule, new liquidity could be created only to finance real goods in the course of production and distribution (Asso et al., 2007). A turning point in the 20th century monetary economics was the recommendation by Milton Friedman (1960) that the money supply should be increased by a fixed percentage every time period. This rule is popularly known as *Friedman's k-percent rule*.

The intellectual debate of *rules versus discretion* is nearly as old as monetary policy rules.[7] Stanley Fischer (1990) noted that, the pre-1977 arguments for rules lacked any convincing demonstration to justify that rules might systematically be better than discretion. The turning point in this debate occurred in 1977 with the seminal paper of Kydland and Prescott (1977): *Rules rather than Discretion: the Inconsistency of Optimal Plans*, in which the authors demonstrated that rules produce time-consistent outcomes if the policy maker's announcement is credible. On the other hand, discretion is time-inconsistent. Although empirical evidence is inconclusive, much of it is in favour of rules over discretion.[8]

Monetary policy rules can broadly be categorised into two as follows: *Instrument Rules* and *Targeting Rules*. The debate as to which one is superior, is ongoing. An instrument rule is generally a simple formula for setting the central bank monetary policy instrument, such as the short-term nominal interest rate. In contrast, a targeting rule is more complex. A targeting rule, in general, specifies objectives to be achieved by listing the target variables (such as inflation) and corresponding targets (such as inflation target) and identifies a loss function that should be minimised (see Svensson, 2003, p.429). The opponents of instrument rules, such as Svensson (2003), argue that if the central bank announces an instrument rule, it has to follow the rule mechanically and there is no room for using

conomic performance and likely monetary policy actions (for an application see Fujiwara and Waki, 2016). Odyssean forward guidance can further be categorised into two, namely, *calendar-based forward guidance* and *threshold-based forward guidance*. In calendar-based forward guidance, the central bank commits to maintaining zero interest rate policy for a fixed duration. In threshold-based forward guidance, the monetary authority announces maintaining interest rates at the ZLB until a pre-announced variable breaches a pre-determined threshold. The present study analyses a variance of threshold-based forward guidance.

[6] See Asso et al. (2007).

[7] See Fischer (1990).

[8] In a recent analysis, John B. Taylor (2012) argues that the recent monetary policy in the United States can be divided into two: first, a rule-based era from 1985 to 2003, then an ad hoc era from 2003 to 2012 characterised by discretionary policy. The stable economic conditions during the first era, and the generally poor economic conditions during the second era, lead him to conclude that rules are preferable to discretion.

judgement. The proponents of instrument rules oppose this argument by pointing out that monetary policy rules, in general, suggest that rules should be used as guidelines or general policy frameworks, rather than mechanical mathematical formulae (see Taylor, 2000).

The celebrated Taylor rule is an interest rate instrument rule proposed by the prominent macroeconomist John B. Taylor in 1993. The rule successfully describes the Federal Reserve Bank of the USA (Fed) interest policy during the period of 1987-1992. The Taylor rule is considered as a good estimation of the Fed policy under normal circumstances, but as with many other rules, it fails during recessions in the presence of liquidity traps. Under such challenging economic conditions, the Taylor rule generally prescribes large negative nominal interest rates. Although small negative nominal interest rates have been exercised in a limited number of central banks recently, the consensus is that large negative interest rates are not feasible.[9] In a liquidity trap with the ZLB constraint, a natural extension of the Taylor rule, often referred to as *the truncated Taylor rule* (TTR), has been proposed by scholars. The TTR simply prescribes zero nominal interest rates whenever the Taylor rule prescribes negative rates.

The ZLB constraint was initially incorporated into perfect foresight models where agents never expecting liquidity traps in the future (for example, see Eggertsson and Woodford, 2003). However, with the inclusion of the ZLB as an occasionally binding constraint, previous results of perfect foresight models changed (see Adam and Billi, 2006, 2007 and Nakov, 2008). The main result found with the inclusion of uncertainty is *the deflation bias* at the steady state. This steady state was later named *the risky steady state* by Coeurdacier et al. (2011) who define the risky steady state as follows: "The risky steady state is the point where agents choose to stay at a given date if they expect future risk and if the realization of shocks is zero at this date" (Coeurdacier et al., 2011, p.398). Scholars argue that the deflation bias risky steady state found in this literature can explain lower inflation –lower than the target inflation rate– observed in many countries including the USA following the Great Recession. They further argue that, following the Great Recession, attaining inflation targets has been harder than before. This is because, the recent ZLB event may have led the agents to revise upward their assessment of the ZLB risk (see Hills et al., 2016).

It has been well documented that the cost channel of monetary policy affects the *optimal* conduct of monetary policy in important ways (for example, see Ravenna and Walsh, 2006). Further, as shown

[9] Economic agents may not lend under large negative nominal interest rate conditions due to the opportunity cost. They may prefer to hold cash.

in Pathberiya (2016) and in Chattopadhyay and Ghosh (2016), the existence of the cost channel affects the optimal monetary policy decisions at the ZLB. Specifically, in Pathberiya (2016) , I show that an optimal discretionary policy requires central banks to keep interest rates at the zero level for longer while an optimal commitment policy requires central banks to terminate zero interest rates earlier in a cost channel economy compared to a no-cost channel economy.

A natural question that arises at this point is what the behaviour of the main macroeconomic variables would be when a central bank is assumed to be following a monetary policy rule, such as the TTR, in a cost channel economy at the ZLB. To the best of my knowledge, this question has not been examined before. This is important because the cost channel accelerates the drop in inflation during a negative demand shock, which feeds back directly into nominal interest rates through the interest rate rule. This mechanism with the cost channel may alter previous results under monetary policy rules at the ZLB.

Accordingly, the main objective of this study is to perform a quantitative analysis to examine the conduct of monetary policy under interest rate rules in a cost channel economy at the ZLB. The ZLB is considered as an occasionally binding constraint.

The other objective of this study is to study an endogenous threshold-based forward guidance policy rule to examine whether that policy rule is able to improve economic conditions during a recession as well as at the steady state. This FG rule is largely motivated by the threshold-based forward guidance carried out by the Fed in December, 2012. In that monetary policy exercise, the Fed announced that it would not exit a zero interest rates policy regime until the unemployment rate dropped to 6.5%.[10] This announcement was a surprise. However, in the present study, forward guidance is considered as an anticipated policy rule accompanied by the TTR. The novelty of this rule is, it is anticipated and endogenous. This fact could affect the steady state values of the variables. In the previous literature, forward guidance has mostly been studied as an exogenous transitory unanticipated shock. By construction, this kind of transitory unanticipated forward guidance does not affect the steady state.

To achieve the above objectives, I consider a reduced-form rational expectations New Keynesian model with the cost channel. I assume that the ZLB constraint is occasionally binding. The model

[10]The Fed's December, 2012 monetary policy statement was recorded as follows: "In particular, the Committee also decided today to keep the target range for the federal funds rate at 0 to 1/4 percent and currently anticipates that this exceptionally low range for the federal funds rate will be appropriate at least as long as the unemployment rate remains above 6-1/2 percent..." (see Fed, 2012).

is log-linearised; the only non-linearity comes from the monetary policy reaction function. Since the non-linear model is stochastic in nature and the ZLB binds occasionally, no analytical solution exists. Therefore, I resort to a numerical method to solve the model. Specifically, I use the numerical approximation method called *the collocation method*, which is discussed in Section 4.1.

The main results are as follows: The cost channel economy is more likely to fall into a liquidity trap and remain there longer under the TTR compared to a no-cost channel economy. This fact, and the amplified asymmetry in expected production costs make the deflation bias large in the risky steady state in cost channel economies compared to that of no-cost channel economies. The welfare loss is higher when uncertainty is high and the welfare loss is appreciably higher in cost channel economies compared to no-cost channel economies. These results suggest that achieving the inflation target in cost channel economies is more challenging than in no-cost channel economies, if agents expect future liquidity traps.

The FG rule can avoid the deflation bias in the risky steady state; indeed, under strict forward guidance, the economy might experience *an inflation bias*. This happens by managing private sector expectations. The FG rule reduces the probability of hitting the ZLB compared to that of the TTR. Furthermore, a recession under the FG rule is less painful and welfare maximising compared to the TTR policy. The above results under forward guidance hold irrespective of the existence of a cost channel. The cost channel increases the inflation bias at the risky steady state under the FG rule.

The rest of the paper is organised as follows: In Section 2, I review the relevant literature on monetary policy rules at the ZLB and forward guidance. Section 3 describes the model, while Section 4 discusses the solution method and parametrisation of the model. The model simulations and results are given in Section 5 while Section 6 concludes the study.

2 Literature Review

Monetary policy strategies in the presence of the ZLB have been studied extensively in the economics literature. In general, the literature suggests that a purely forward-looking approach to policy can lead to bad outcomes in a liquidity-trapped recession following a negative demand shock (for example, see Eggertsson and Woodford, 2003).

However, many studies, including the study cited above, assume perfect foresight. Perfect foresight is a fair benchmark. Yet, in that setting, it is assumed that agents never expect the ZLB to be reached in the future. Adam and Billi (2006, 2007), Nakov (2008) and Hills et al. (2016), among others, have considered both optimal monetary policy and monetary policy rules in a stochastic setting with uncertainty. In the stochastic setting, the ZLB is considered as an occasionally binding constraint. Surprisingly, when the ZLB is considered as an occasionally binding constraint, not only do the previous results about the recession change, but importantly, the steady state is different from the deterministic steady state. This steady state under uncertainty is called *the risky steady state.* The main result found in this literature, which incorporates uncertainty by way of occasionally binding ZLB constraint, is the existence of *a deflation bias* in the risky steady state (for example, see Adam and Billi, 2006, 2007 and Nakov, 2008). A deflation bias at the steady state is observed because, the expected cost of production is distributed asymmetrically in the steady state as agents expect the ZLB occurrences in the future. When the expected marginal cost is less due to the ZLB, pricing decisions of firms today are affected, resulting in the deflation bias steady state.

It is well established that when the ZLB is considered, under interest rate rules, there can be multiple equilibria (for example, see Benhabib et al., 2001). Generally, studies have shown that there can be a bad deflationary steady state with the deflationary liquidity-trap and a good steady state with inflation achieving its target. The bad deflationary steady state and the risky steady state are different. The risky steady state is generally a deviation from deterministic steady state whereas the bad deflationary steady state itself is a unique deterministic steady state.

According to Taylor and Williams (2010), research has identified four important implications of interest rate rules at the ZLB. First, the interest rate rule should be modified to incorporate the ZLB. This modification is normally termed as *the truncated interest rate rule,* which introduces an additional non-linearity to the model. Second, the ZLB can imply multiple steady states, which is discussed above. Third, the ZLB may have implications for the parametrisation of the monetary policy reaction function. For example, increasing the response to the output gap helps reduce the effects of the ZLB. Fourth, the ZLB provides a case for higher target inflation.

Sugo and Teranishi (2005) examined the *optimal monetary policy rules* at the ZLB. They considered three interest rate rules in their exercise. These rules consist of variables such as the inflation rate, the output gap and their lags, including the lag of the nominal interest rate. The rules examined by Sugo and Teransihi have been shown to be optimal by Giannoni and Woodford (2002) under no-ZLB constraint. Sugo and Teranishi showed that optimal rules, which ignore the ZLB constraint, do not always remain optimal with the ZLB constraint. However, the only exception they found was the interest rate rule which does not include lagged nominal interest rate. That rule remains optimal regardless of the ZLB constraint.

The impact of the cost channel under monetary policy rules at the ZLB has not been exclusively studied. However, the impact of the cost channel on monetary policy rules under normal conditions, i.e. without the ZLB constraint, has been studied. Llosa and Tuesta (2009), Surico (2008) and Brückner and Schabert (2003) have shown that in existence of the cost channel, Taylor-type instrument rules may induce indeterminacy. Llosa and Tuesta (2009) have particularly considered two variations of the Taylor rule, i.e. contemporaneous and forward-looking rules. They have shown that determinacy may only be attainable if the central bank reacts modestly to both the output gap and inflation expectations in a cost channel model.

In practice, forward guidance has been instrumental in stimulating the economy at the ZLB, especially in the Great Recession (see Smith and Becker, 2015). In the monetary policy modeling, forward guidance is generally incorporated into the models in a few different ways. The first way is with an optimal commitment policy, in which the general public is informed of the state-contingent policy plan of the central bank (see Eggertsson and Woodford, 2003). However, such a policy is non-trivial to implement. This is because, it may not be feasible to provide a complete description of all possible state-contingent future interest rate paths. Although it was possible to write down these policy paths, yet, it would be difficult to explain it to the general public (see Eggertsson and Woodford, 2003, p.181). The second way is to incorporate forward guidance as an external news shock to nominal interest rates (see Laséen and Svensson, 2011). The third way is to incorporate forward guidance as an exogenous extension to the zero interest rate regime (see Chattopadhyay and Daniel, 2015). The fourth way is to incorporate forward guidance endogenously by augmenting the monetary policy rule, such as the Taylor rule (see Reifschneider and Williams, 2000 and Katagiri, 2016).

The fifth way to incorporate forward guidance into models is to assume that the central bank announces a transitory endogenous rule (see Boneva et al., 2015). In this form of forward guidance, the central bank announces either threshold-based or calendar-based forward guidance during a liquidity trap. This announcement is entirely unanticipated. This kind of forward guidance is more closer to the practical forward guidance exercises under Odyssean forward guidance. Boneva et al. (2015), using their model, have showed that the threshold-based forward guidance is superior to the purely calendar-based forward guidance. They have considered a New Keynesian model with optimal monetary policy.

The FG rule proposed in the present study is closer to the fifth category. However, in contrast, the present FG rule is not unanticipated. The FG rule in this study is informed to agents by the central bank at time zero; accordingly agents form expectations.

3 The Model

The economy is represented by three blocks, as is standard in the New Keynesian literature. They are: an aggregate demand block represented by the dynamic IS equation (DIS), an aggregate supply block represented by the New Keynesian Phillips curve (NKPC) and the monetary policy block. To incorporate the cost channel, I assume that a portion of the cost of the working capital must be financed by firms externally at the beginning of the period.

3.1 Aggregate Demand and Aggregate Supply Blocks

The aggregate demand and the aggregate supply blocks considered in this paper are standard in new Keynesian literature. Accordingly, the DIS is given by:

$$x_t = E_t x_{t+1} - \sigma^{-1}\left[\hat{R}_t - E_t\pi_{t+1} - \hat{r_t^n}\right],$$

and NKPC with the cost channel is given by:

$$\pi_t = \beta E_t\pi_{t+1} + \kappa(\sigma+\eta)x_t + \kappa J\hat{R_t},$$

where x_t is the output gap, π_t is the rate of inflation between time $t-1$ and t. $\hat{R}_t$ and $\hat{r_t^n}$ are the percentage point deviation of nominal interest rate and natural interest rate from their corresponding zero inflation steady state values, respectively. $\beta \in (0,1)$ is a subjective rate of discount, $\sigma > 0$ is the coefficient of relative risk aversion and $\eta > 0$ is the elasticity of labour supply. The slope parameter of the NKPC: $\kappa = \frac{(1-\omega)(1-\omega\beta)}{\omega}$, where ω is share of firms that cannot adjust prices optimally.

The parameter $J \in [0,1]$ in the NKPC represents the cost channel of monetary policy. It denotes the portion of the wage bill covered by firms using external short-term loans taken out at the beginning of time t. These loans are to be settled within the time period t. For example, $J=1$ means firms borrow the full wage bill externally. On the other hand, $J=0$ means firms do not take out loans externally to cover the wage bill.

3.2 Monetary Policy Block

Two types of monetary policies are considered in this study. One is truncated Taylor-type rules and the other one is a forward guidance rule.

3.2.1 Truncated Taylor-Type Rules

In the baseline model, it is assumed that monetary policy is conducted using a truncated Taylor rule with contemporaneous inflation and contemporaneous output gap variables (i.e. contemporaneous truncated Taylor rule, for short CTTR). Accordingly, the CTTR constrained by the ZLB is given by:

$$R_t = max[1, r^* + \pi^* + \phi_\pi(\pi_t - \pi^*) + \phi_x x_t],$$

where R_t is the gross nominal interest rate, r^* is the equilibrium real gross interest rate, π^* is the target inflation rate, ϕ_π is the inflation response coefficient and ϕ_x is the output gap response coefficient.

In addition to that, to examine the robustness of results, three variations of TTRs are considered as follows: a) Backward-looking truncated rule (BLTR): $R_t = max[1, r^* + \pi^* + \phi_\pi(\pi_{t-1} - \pi^*) + \phi_x x_{t-1}]$, b) Forward-looking truncated rule (FLTR): $R_t = max[1, r^* + \pi^* + \phi_\pi(\pi_{t+1} - \pi^*) + \phi_x x_{t+1}]$ and, c) Interest rate smoothing truncated rule (ISTR): $R_t = max[1, \phi_i R_{t-1} + (1 - \phi_i) R_t^{Taylor}]$, where R_t^{Taylor} is the value of the nominal interest rate prescribed by the TTR and ϕ_i is the interest rate smoothing coefficient.

3.2.2 Forward Guidance Rule

I consider an endogenous threshold-based (or data-based) FG rule. Rather than considering an exogenous shock, here I consider a state-contingent rule-based forward guidance which activates endogenously, according to economic conditions. In normal times, the central bank conducts monetary policy following a TTR. However, the central bank promises to maintain a fixed policy rate (for example, zero nominal interest rates) until a specific event occurs whenever the economy moves to a liquidity trap. For example, the central bank may promise to hold interest rates at the zero level until the unemployment rate breaches a certain threshold following a recession. This forward guidance announcement is made at time zero. Therefore, it is permanent and anticipated by the general public. This is different from the normal forward guidance policy experiments found in the literature. In the literature, in general, the forward guidance policy announcement is entirely unanticipated and transitory.

Specifically, under the present FG rule, I consider that the central bank credibly announces the following: that it will keep interest rates at the zero level until the lagged output gap recovers to a certain level following the liquidity trap. At the exit of the zero interest rate policy, following a recession, the central bank promises to follow the TTR as before. More formally, the FG rule can be stated as follows:

$$R_t = 1 \quad \text{if} \quad \left[R_t^{Taylor} \leq 1\right] \quad \text{or} \quad \left[R_{t-1} = 1 \text{ and } x_{t-1} < a\right],$$

$$R_t = R_t^{Taylor} \quad \text{otherwise},$$

where $a < 0$ is a value chosen by the central bank. If the central bank chooses a large value for a, that is considered as *strict forward guidance,* while if the central bank chooses a small value for a, that is considered as *weak forward guidance*.

According to this rule, whenever the TTR prescribes zero interest rates, the central bank moves to the zero interest rate regime from the non-zero policy rate regime. However, return from the zero interest rate regime is not exclusively based on the TTR. The central bank agrees to keep the zero interest regime longer, until the previous period output gap has breached a pre-specified threshold level.

3.3 Shock Process

The economy is prone to be hit by a stochastic shock to the natural interest rate. The natural interest rate is assumed to follow an exogenous mean reverting process, as specified by Nakov (2008) in the aftermath of the shock, as follows:

$$\hat{r_t^n} = \rho \hat{r}_{t-1}^n + \epsilon_t,$$

where ϵ_t is i.i.d. $N(0, \sigma_\epsilon^2)$, σ_ϵ^2 is the variance of the shock and $\rho \in (0, 1)$ is the persistence parameter.

Due to the stochastic nature of the shock process, the non-negativity constraint of the nominal interest rate may bind occasionally.

3.4 Welfare Calculation

The welfare calculation is based on the procedure used by Adam and Billi (2007, p.748). Accordingly, the utility equivalent percentage loss of consumption in the steady state is given by, $p = 100 * \frac{1}{\sigma}\left(-1+\sqrt{1+\frac{2(1-\beta)L'}{1/\sigma}}\right)$. Here, $L' = \frac{1}{2}\frac{\omega\theta(1+\zeta\theta)}{(1-\omega)(1-\omega\beta)}\sum_{i=0}^{\infty}\beta^i(\pi_{t+i}^2 + \lambda x_{t+i}^2)$, where, λ is the weight assigned to the output gap in the monetary authority's objective function,[11] ζ is elasticity of a firm's real marginal cost and θ is the elasticity of substitution among production varieties.[12]

The welfare maximising condition for the loss function used in the welfare calculation requires inflation and the output gap take zero values. Since both inflation and the output gap take non-zero values at the risky steady state, welfare is not maximised at risky steady states.

4 Solution Method and Calibration

This section describes the solution method used in this study and the model calibration.

4.1 Solution Method

Since the proposed non-linear rational expectations model is stochastic in nature and the ZLB binds occasionally, no analytical solution is possible. Therefore, I resort to a numerical method to solve the model. I use the numerical approximation method called *the collocation method*. This methodology has been widely used in past studies including Nakov (2008), Adam and Billi (2006, 2007), Gavin et al. (2013), Boneva et al. (2015) and Joo (2010) to solve models with occasionally binding ZLB constraint.

Any numerical method has its own advantages and disadvantages. The main advantage of collocation is, it is a global method, which is appropriate for analysing the proposed stochastic model with an

[11]The monetary authority's loss function takes the form: $L_0 = -\frac{1}{2}E_0\sum_{t=0}^{\infty}\beta^t\left\{\pi_t^2 + \lambda x_t^2\right\}$. This loss function has been derived using a second-order Taylor expansion of the utility of the representative household. Woodford (2003) derives this for a standard New Keynesian model, while Ravenna and Walsh (2006) derive it for a New Keynesian model with the cost channel, which is similar to the present model.

[12]Following Adam and Billi (2007), I set $\lambda = 0.003$, $\theta = 7.66$, $\zeta = 0.47$ for the welfare calculation under Section 5.

occasionally binding constraint. Further, the collocation method is flexible, accurate and numerically efficient compared to the more commonly used linear-quadratic approximation method (see Miranda and Fackler, 2004, Chapter 9).

There are two main disadvantages of collocation. In the context of the ZLB constraint, it is known that there can be multiple equilibria. However, the collocation method would solve only for one of them.[13] Second, this methodology may not be able to compute an equilibrium for a certain region in the parameter space. For example, Richter and Throckmorton (2015), with a fully non-linear model, report that when the persistence of the shock process increases, the standard deviation of the innovation should decline to avoid a non-convergence region.[14] However, the latter issue is not exclusively relevant to the collocation method.

The following is a brief description of the collocation method. Readers may refer to Miranda and Fackler (2004, Chapter 9) or McGrattan (2001) for a general description about the collocation method or Nakov (2008) for more specific details relevant to the context of this study.

The rational expectation problem at our hand is to solve for the policy plan, x_t, when equilibrium responses are given by the complementary condition:

$$f[s_t, x_t, E_t h(s_{t+1}, x_{t+1}), a(s_t), b(s_t)] = \phi_t,$$

with the state transition function: $s_{t+1} = g(s_t, x_t, \epsilon_{t+1})$, where $h[s, x(s)]$ is the expectation function to be approximated[15] and ϵ_{t+1} is the exogenous shock.

Note that x_t and ϕ_t satisfy the following complementary conditions: $a(s_t) \leq x_t \leq b(s_t)$, $x_{jt} > a_j(s_t) => \phi_{jt} \leq 0$, $x_{jt} < b_j(s_t) => \phi_{jt} \geq 0$, where ϕ_{jt} measures the marginal loss from activity j.

The expectation function is approximated using a linear combination of n basis functions:

$$h([s, x(s)] \approx \sum_{j=1}^{n} c_j \theta_j(s),$$

where θ_j is a known basis function and c_j is basis function coefficient. The coefficient vector c is updated by solving the following system: $\sum_{j=1}^{n} c_j \theta_j(s_i) = h(s_i, x_i)$.

[13]For example, as discussed under Literature Review Section, Benhabib et al. (2001) show that the New Keynesian models constrained by the ZLB can have two deterministic steady state equilibria. The inflation target is met in one steady state while the economy experiences deflation in the other. The solution method that I use in this study, which has been used in the papers cited above, however, does not converge to the deflationary steady state.

[14]I experience the same non-convergence behaviour in the present analysis.

[15]Response function approximation is also possible, but it may lead to difficulties when facing the kink due to the ZLB constraint (see Miranda and Fackler, 2004, p.302).

To approximate the normally distributed shock to the natural interest rate, they are discretised using the K-node Gaussian quadrature scheme.

The endogenous variables relevant to the present study are x_t, π_t and i_t. The endogenous state variables are π_{t-1},x_{t-1} and i_{t-1} while r_t^n is the exogenous state variable.[16]

4.2 Calibration

The model is calibrated using standard parameter values for the US economy as given in Table 4.1. Unless otherwise specified, quarterly parameter values are reported in the table.

Table 4.1: Baseline Calibration

Parameter	Description	Baseline Value
β	Discount rate in the utility function	$\frac{1}{1.0075} = 0.993$
σ	Coefficient of relative risk aversion	4
η	Elasticity of labour supply in the utility function	1
J	Share of working capital to be financed externally	$[0, 1]$
ω	Share of firms that cannot adjust prices optimally	0.85
κ	Slope parameter of the NKPC	0.028
Net Natural rate of interest	Mean (per annum)	$\frac{1}{\beta} - 1 = 3\%$
	Max. depth of the large negative shock (per annum)	-6%
	Standard deviation [per annum, $\sigma(r^n)$]	3
	Shock persistence (ρ)	0.65
Taylor Rule	Inflation Target (per annum)	0%
	Coefficient on inflation (ϕ_π)	1.5
	Coefficient on output (ϕ_x)	1
FG Rule	Output gap threshold (a)	-0.25%

Few parameter values are worth noting here. Following Woodford (2003), the discount rate (β) has been set at 0.993 to be compatible with the mean value of natural interest rate of 3% annually. The standard deviation of the natural interest rate is set at 3 (annually), which ensures the probability of hitting the ZLB under the baseline calibration for the no-cost channel economy is approximately 6%. Following Nakov (2008), the coefficient of relative risk aversion (σ) is set at 4. The inverse of this parameter, σ^{-1}, is interpreted as the real interest rate elasticity of aggregate demand, which is equal to 0.25. The value of slope parameter of the NKPC is 0.028. This value has been calculated using the formula derived from micro-foundations, as stated in Section 3.1, and the baseline calibration of the structural parameters given in Table 4.1. I consider lower values for the slope parameter under a

[16]The maximum number of state variables used in a simulation in this study is three. For example, in the baseline specification with the CTTR, there are only two state variables; $\pi_{t-1}$and r_t^n. For the forward guidance experiment, there are three state variables involved; $i_{t_{-1}}$, $x_{t-1}$and r_t^n.

separate section (Section 5.5.3.3) to examine the robustness of the results.

In the baseline calibration, following the literature, I have considered a large negative shock to the natural interest rate, with a maximum depth of -6$\%$ annually. The persistence of the shock (ρ) is set at 0.65, which means the natural interest rate would take approximately 15 quarters to recover following the shock.

The Taylor rule parameters, coefficient on inflation (ϕ_π) and coefficient on output (ϕ_x) are set at 1.5 and 1, respectively. The value for ϕ_π is identical to the original Taylor rule parameter in Taylor (1993). However, the value for ϕ_x is different from the original Taylor rule value of 0.5. Former Fed chair Ben Bernanke, as well as current Fed chair Jannet Yellen, among others, propose a higher weight for the output coefficient of the Taylor rule, considering the Federal Open Market Committee's *balanced approach* in responding to inflation and output variations (see Bernanke, 2015 and Yellen, 2012). Accordingly, in the baseline calibration, I consider $\phi_x = 1$.

In the FG rule, I consider $a = -0.25$. This means, the monetary authority delays the exit of the zero interest rate regime until the lagged output gap recovers below 0.25%.

The next section is devoted to reporting simulation outcomes and discussing results.

5 Simulations and Results

5.1 Introduction

In this section, I simulate the model for the baseline specification and carry out robustness checks and sensitivity analysis.[17] First, I specify the path of the natural interest rate in a simulated liquidity-trap. Then, the CTTR is considered in detail and I then compare and contrast the results in a cost channel and a no-cost channel economy. Next, I move to robustness checks and sensitivity analysis under CTTR. Under the robustness check, I consider alternative TTRs and an alternative calibration with a lower value for the slope of the NKPC. Finally, I examine the FG rule and conduct a sensitivity analysis for the FG rule.

[17]Matlab (version R2016a) has been used to facilitate the simulations. The high level Matlab routines developed by Miranda and Fackler (2004) have been used in my codes. These Matlab routines are freely available at: http://www4.ncsu.edu/~pfackler/compecon/toolbox.html under the name CompEcon Toolbox for Matlab. The Matalb codes of Nakov (2008) and Adam and Billi (2006, 2007) were also beneficial for the development of the codes for my model. The Nakov (2008) codes are available at: https://sites.google.com/site/antonnakov/software while the Adam and Billi (2006, 2007) codes are available at: http://www.rmbilli.com/. I am grateful to those authors for making their codes available to the public.

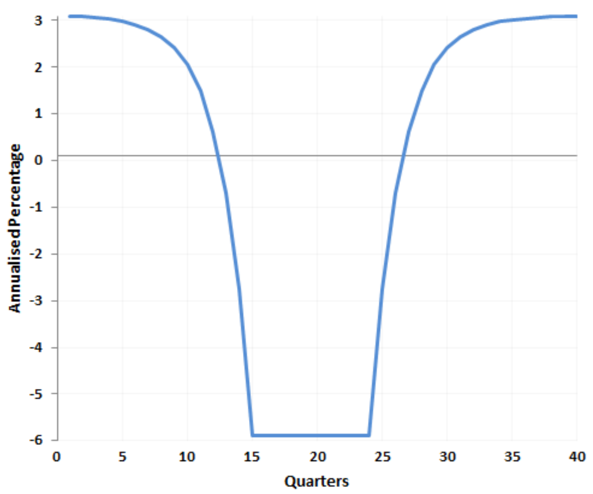
For each specification of the simulation exercise, $20,000$ replications are simulated. Each of those replications is $4,000$ periods long.[18] When calculating the probability of nominal interest rates binding at the zero level, the first $1,000$ periods have been dropped, so disturbance from the initial large negative shock is avoided.

The values reported in tables and figures are in annualised terms. Interest rates are given in net annualised percentages. The baseline parametrisation has been considered for all the simulations, except in robustness checks and the sensitivity analysis.

5.2 Path of the Natural Interest Rate

The dynamic path of the natural interest rate in a simulated liquidity-trap environment is considered in this section. As depicted in Figure 5.1, a large negative exogenous shock to the natural interest rate takes it to its maximum depth of -6$\%$ in the 15th quarter. The natural rate stays at the minimum value for 10 more quarters, before recovering to its steady state value in the next 15 quarters.

Figure 5.1: Path of Net Natural Interest Rate



5.3 Truncated Taylor Rules

The main aim of this section is to analyse the impact of the cost channel on macroeconomic variables when the monetary authority conducts monetary policy with TTRs as defined in Section 3.2.1. For this purpose, I mainly focus on the CTTR. I examine the robustness of the results with alternative

[18] The baseline simulation under the CTTR in the cost channel model took 8 minutes to converge in an Intel Core i7 processor (3.10 GHz, 4 cores) personal computer. The baseline simulation under the FG rule ($a = -0.25$) with the cost channel, took 6.4 hours to converge.

TTRs as defined in Section 3.2.1.

5.3.1 Contemporaneous Truncated Taylor Rule

The CTTR is analysed in this section. First, the case without the ZLB constraint is considered, then I move to the case with the ZLB constraint.

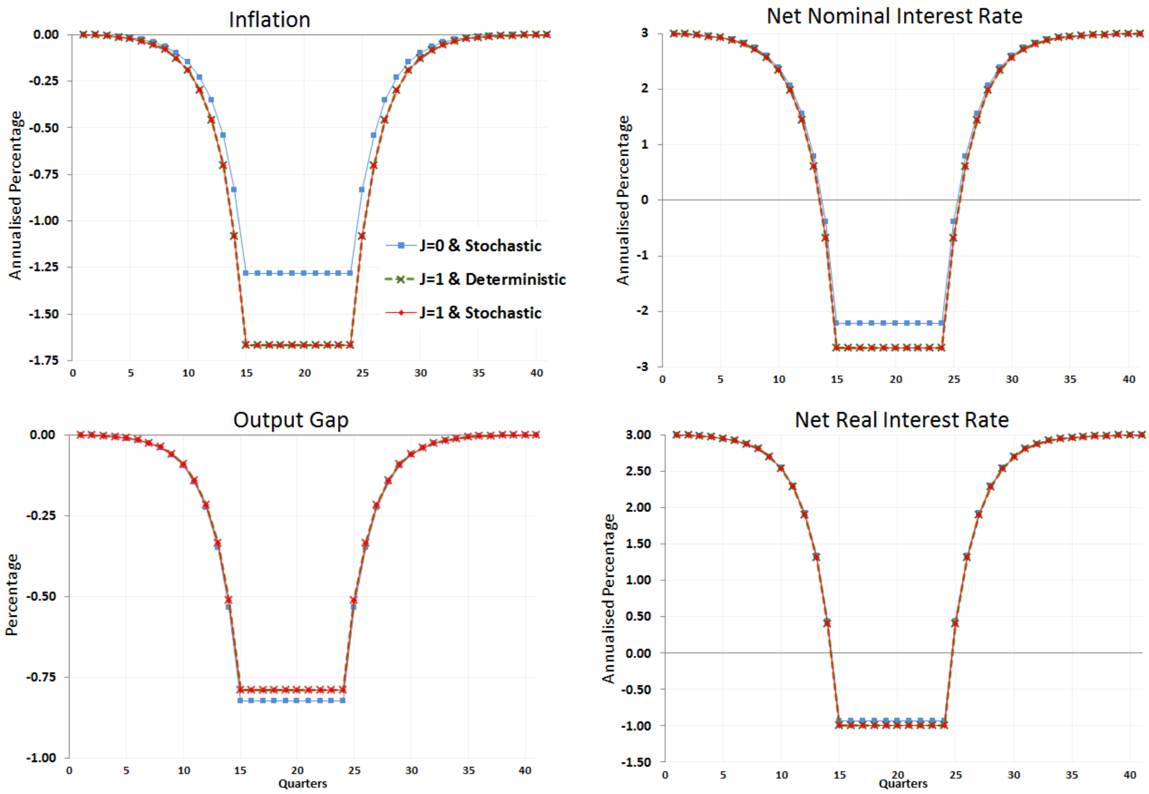
Analysis without the ZLB Constraint

In this section, it is assumed that policy interest rates are not constrained by the ZLB. The two polar cases, i.e. the case $J = 0$ and the case $J = 1$ are considered. Recall, $J = 1$ assumes that firms borrow all of their working capital requirements externally in advance, while $J = 0$ assumes firms do not borrow externally for working capital purposes. I also consider both the deterministic scenario [$\sigma(r^n) = 0$] and the baseline stochastic specification [$\sigma(r^n) = 3$, annually].

Figure 5.2 depicts the paths of four simulated variables, i.e. inflation, net nominal interest rate, output gap and net real interest rate during the negative demand shock period. Three scenarios are considered; cost channel (red line with diamonds) and no-cost channel (blue line with squares) economies in a stochastic setting, and a cost channel economy in a deterministic setting (green line with crosses). According to the figure, basically, all four variables in all three scenarios follow the behaviour of the natural interest rate. In addition, the figure shows that paths of variables are almost identical in the stochastic and the deterministic setting in cost channel economies. This is true for the no-cost channel economy as well, which has not been shown in the figure. Further, the stochastic steady state values of variables are identical to the deterministic steady state values, irrespective of the cost channel. These results show that uncertainty does not matter significantly in this set-up, if the ZLB constraint is not taken into consideration.

Figure 5.2 further shows that the cost channel economy is more deflationary in a recession than the no-cost channel economy. This is because, during the shock period when the central bank cuts interest rates, the marginal cost of production drops more in cost channel economies than in no-cost channel economies, resulting a larger drop in inflation.

Figure 5.2: Paths of Variables under CTTR - No ZLB Constraint



Note: Baseline calibration has been used without the ZLB constraint on nominal interest rates.
In the deterministic setting, standard deviation of the natural interest rate has been set to zero.

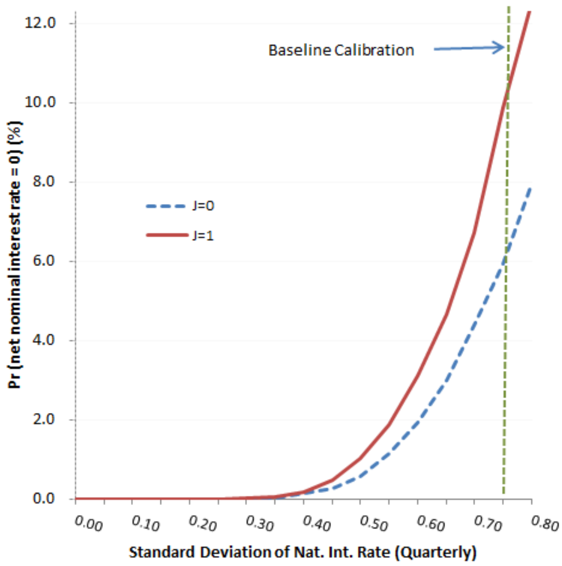
Analysis with the ZLB Constraint

This section carries out one of the most important analyses of this study, i.e. the analysis with the ZLB constraint under the CTTR.

First, I consider the probability of the policy rate hitting the ZLB in a cost channel economy as well as in a no-cost channel economy. Figure 5.3 depicts relationship between probability of hitting the ZLB against the standard deviation of natural interest rate. The figure shows that, as expected, the increase in uncertainty increases the probability of hitting the ZLB exponentially. For the baseline calibration in a no-cost channel economy, the probability of hitting the ZLB is 5.9% (see Table 5.1 for values). This means that there is a possibility of approaching a liquidity trap in around six years during a 100 year period. As the figure shows, the important finding is that the probability of hitting the ZLB in the cost channel economy is equal to or higher than the probability of hitting it in the no-cost channel economy; the higher the uncertainty, the greater the difference. For example, under the baseline calibration, the likelihood of the cost channel economy hitting the ZLB is 9.9%, which is 4 percentage points or 66.6% higher than a no-cost channel economy. The reason is as follows:

Irrespective of the cost channel, when the economy is hit by a large negative demand shock, agents expect lower future inflation. This would lower current inflation, thereby lowering nominal interest rates as the central bank is following a TTR. This action validates agents' previous lower expected inflation figures, prompting them to further lower their inflation expectations and so on. In addition to that, in cost channel economies, current inflation drops further due to the direct impact of the interest rate cut on production costs through the cost channel. Accordingly, the central bank in the cost channel economy has to cut interest rates more in the second cycle and on. Accordingly, cost channel economies are more likely to hit the ZLB than no-cost channel economies.

Figure 5.3: Std. Dev. of Natural Interest Rate Vs Probability of Hitting the ZLB



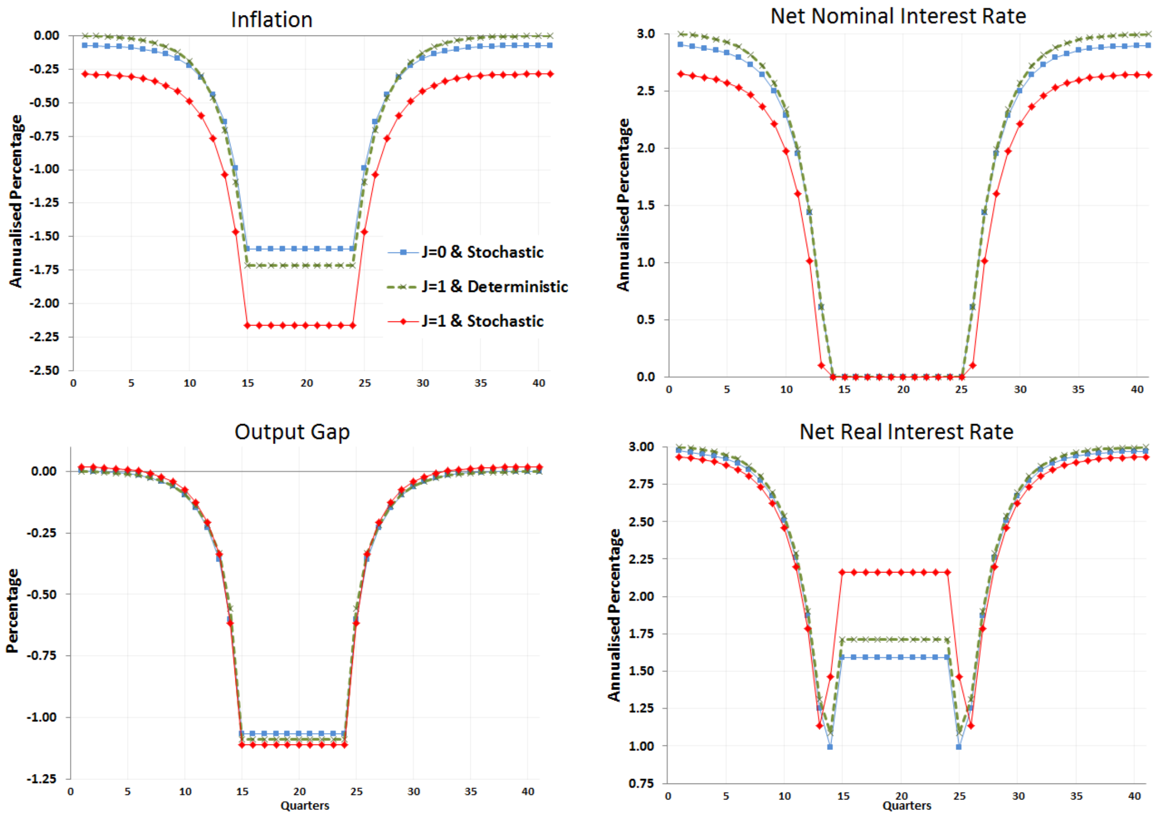
Now I move to the analysis of the paths of variables in a liquidity trap scenario under the ZLB constraint. First, I consider the path of inflation in a cost channel economy in a deterministic setting. This is depicted by the green line with crosses in the top left panel of Figure 5.4. This line shows that the deterministic steady state achieves the inflation target of 0%. This result is true for the no-cost channel economy as well, which is not shown in the figure.

The path of inflation in a stochastic no-cost channel economy is depicted by the blue line with squares in the top left panel of Figure 5.4. In general, inflation follows the path of the natural interest rate. However, note that the steady state value of inflation is not the deterministic steady state value. This is the *risky steady state*. The asymmetry introduced by the ZLB constraint causes inflation to undershoot its target. This happens as follows: When the economy hits with a large negative shock, the ZLB binds; therefore, the additional decline in the real wage will not be contained.[19] However,

[19] Additional decline in real wages at the ZLB occurs as follows: Since the nominal interest rate is stuck at the zero level

in contrast, due to a large positive shock, upward adjustments in the policy rate will partially temper the subsequent increase in real wages. Therefore, under uncertainty, this asymmetry in real wages lowers expected real wages and in turn reduces the expected cost of production at the steady state. That is, the ZLB makes the distribution of the cost of production asymmetric. This makes expected production costs lower compared to the no-ZLB constraint scenario, leading forward-looking private sector firms to reduce current prices. A reduction in prices reduces current inflation, even though no shock has actually happened. This produces the deflation bias at the steady state (see Hills et al., 2016, pp.9-10). This mechanism is further elaborated upon in the positive shock analysis later in this section.

Figure 5.4: Paths of Variables under CTTR - With the ZLB Constraint



Note: Baseline calibration. In the deterministic setting, standard deviation of the natural interest rate has been set to zero.

The red line with diamonds in the top left panel of Figure 5.4 depicts the path of inflation in a cost channel economy under uncertainty. This line shows that the risky steady state inflation is around 21 basis points lower in the cost channel economy compared to the no-cost channel economy. Further, inflation in the cost channel economy also follows the behaviour of the natural interest rate,

and households revise inflation expectations downwards, real interest rates increase. Increase in real interest rates reduces household consumption, lowering aggregate demand. Firms respond to the lower aggregate demand by reducing prices and cutting down labour demand. This mechanism reduces the real wage at the ZLB compared to the no-ZLB constraint scenario (see Gavin et al., 2015, p.22).

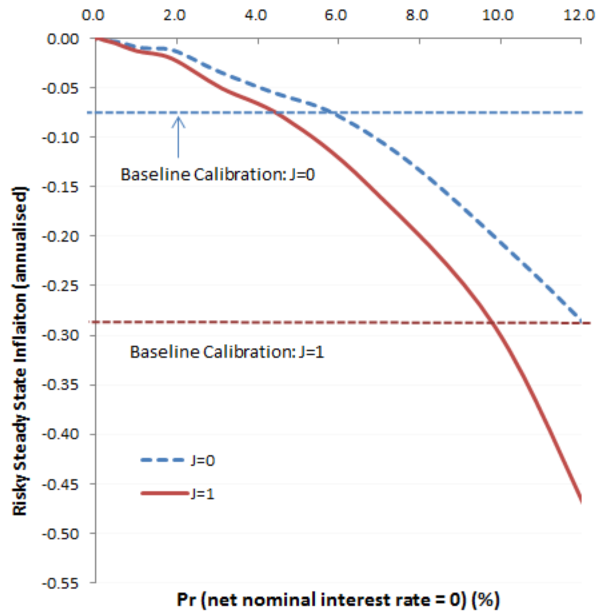
although deflation is higher than in no-cost channel economies throughout the simulation. The larger deflation bias in the cost channel economy in the risky steady state arises for two reasons. First, the real interest rate is higher in the liquidity trap in cost channel economies than in no-cost channel economies (this is evident from the bottom left panel of Figure 5.4). This higher real interest rate in the cost channel economy amplifies the asymmetry in production costs more than in no-cost channel economies. Second, as observed earlier, the probability of hitting the ZLB in cost channel economies is higher than in no-cost channel economies. This makes agents expect more recessions in the future. This effect further amplifies the asymmetry in expected production costs compared to no-cost channel economies. These two causes result in a higher deflation bias in cost channel economies at the risky steady state.

The top right panel of Figure 5.4 shows the path of nominal interest rates. In the risky steady state, the nominal interest rate is lower than the deterministic steady state in both economies. This happens because inflation is lower than the target rate in the risky steady state. Accordingly, the CTTR prescribes a lower nominal interest rate than in the deterministic steady state.

The bottom left panel of Figure 5.4 depicts the path of the output gap. The figure shows that during the liquidity-trap, the output gap in the stochastic case is higher than in the deterministic case in a cost channel economy. This is because, irrespective of the cost channel, the real interest rate is higher, in turn, the output gap is higher in the stochastic case than in the deterministic case due to higher deflation. Further, the output gap is higher in the cost channel economy than in the no-cost channel economy, because the real interest rate is high in the cost channel economy.

To investigate the risky steady state inflation further, I plot the probability of hitting the ZLB and risky steady state inflation in Figure 5.5. The figure clearly shows that there is a significant difference between risky steady states in cost channel and no-cost channel economies when the uncertainty is high.

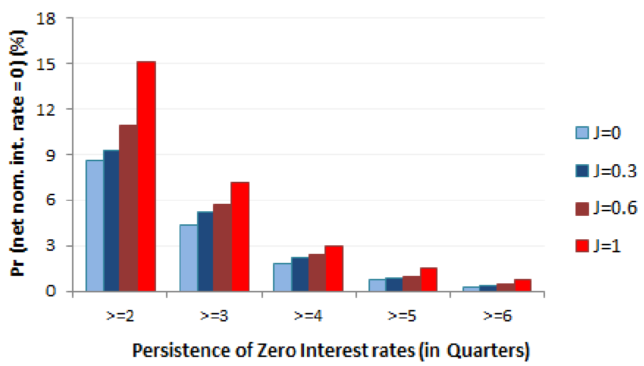
Figure 5.5: Probability of Hitting the ZLB Vs Steady State Inflation



Persistence of the Zero Lower Bound for Different Values of J

The probability of the persistence of the ZLB is discussed in this section. This probability is conditional on interest rates being binding at the zero level in quarter one following a negative demand shock. The probability of the persistence of the ZLB for different values of J is plotted in Figure 5.6. Note that $J = 0.6$ is considered as the empirically relevant value for the US economy.[20] The figure shows that when the ZLB is binding, interest rates remain at the ZLB longer in cost channel economies, than in no-cost channel economies.

Figure 5.6: Probability of Persistence of the ZLB Conditional on Interest Rates Being Binding in Q1



Note: Highest persistence for J=1 is 21 quarters while for J=0 is 16 quarters. Baseline calibration.

[20] As mentioned before, Christiano et al. (2015) estimated that firms borrowed around 56.2% of their working capital externally in the post-war USA economy. Accordingly, I consider the more empirically relevant value of $J = 0.6$.

Macroeconomic Performances under the CTTR for Different Values of J

Figure 5.7 and the corresponding Table 5.1 display paths of variables and macroeconomic performances, respectively, under the CTTR for different strengths of the cost channel in the economy. The figure shows that the higher the value of J, or in other words, the stronger the cost channel in the economy, any recession is relatively more severe and deviations from the deterministic steady state are larger. When $J = 0.6$, inflation undershoots about 16 basis points from its deterministic steady state value.

Figure 5.7: Paths of Variables under CTTR for Different Values of J

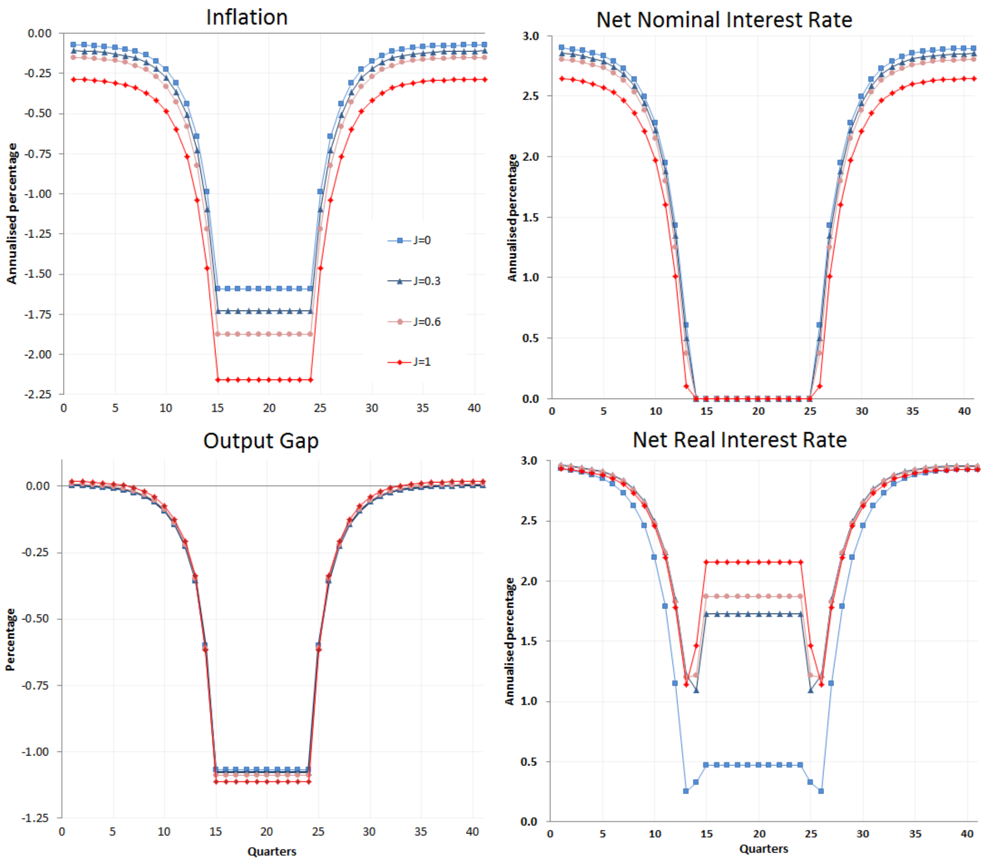


Table 5.1 shows that the value of J and the probability of hitting the ZLB are positively correlated. Further, it shows when the cost channel is present in the economy, standard deviations of macroeconomic variables are higher. The welfare analysis shows that the higher the uncertainty, the higher the welfare loss. Further, the welfare loss is significantly high in cost channel economies compared to no-cost channel economies. For example, Table 5.1 shows that the welfare loss in the full cost channel economy is almost four times higher than the loss in the no-cost channel economy.

Table 5.1: Macroeconomic Performances under CTTR for Different Values of J

Measure	Value of J			
	0	0.3	0.6	1
% of time net Nom. Interest rate bounded by Zero	5.92	6.75	7.67	9.86
Lowest value (%):				
Net Nominal Interest Rate	0.00	0.00	0.00	0.00
Inflation	-1.59	-1.73	-1.87	-2.16
Output Gap	-1.07	-1.08	-1.09	-1.11
Steady state value (%) of:				
Net Nominal Interest Rate	2.87	2.83	2.77	2.60
Inflation	-0.08	-0.11	-0.16	-0.29
Output Gap	-0.003	0.000	0.000	0.009
Standard Deviation[1/] of:				
Nominal Interest Rate	1.706	X 1.02	X 1.04	X 1.06
Inflation	0.453	X 1.08	X 1.17	X 1.30
Output Gap	0.290	X 1.00	X 1.00	X 1.00
Welfare loss[1/]	0.016	X 1.34	X 1.83	X 3.84

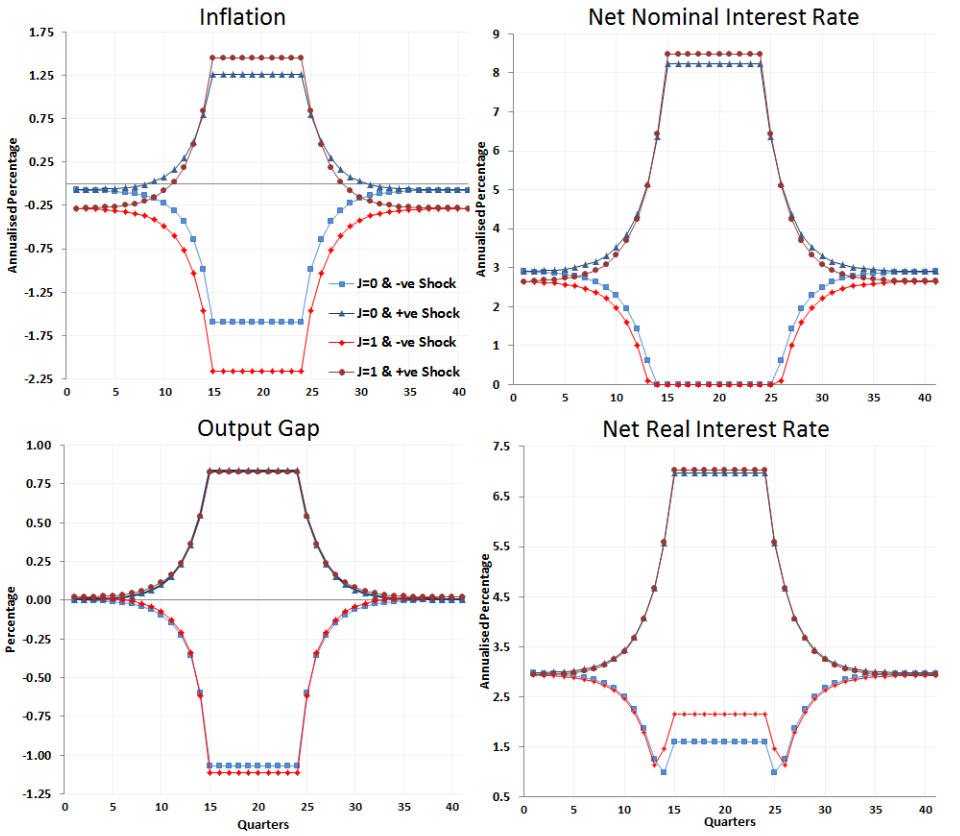
1/ Relative to the case J=0.

Baseline calibration - for different values of J.

Analysis with a Large Positive Shock to the Economy

Paths of variables under a corresponding large positive shock are considered in this section. For comparison purposes, dynamic paths of variables under both positive and negative shocks in cost channel and no-cost channel economies are depicted in Figure 5.8. It is evident from the figure that drops in both inflation and the output gap are larger due to a negative shock than the corresponding increases due to a positive shock. On the other hand, the drop in the real interest rate is lower in the liquidity trap under a negative shock compared to a corresponding increase under a positive shock. These observations are true for both cost and no-cost economies.

Figure 5.8: Paths of Variables to a Large Positive Shock to the Economy under CTTR



Note: Path of the natural interest rate to a positive shock is symmetric to the negative shock. Accordingly, the maximum value of the net natural interest rate during the liquidity trap is 12%.

To demonstrate the asymmetry in quantitative terms, I tabulate values in Table 5.2. The table gives the absolute maximum change in inflation and the output gap during both negative and positive shocks.[21] Furthermore, the table gives values for both cost and no-cost channel economies. For the no-cost channel (cost channel) economy, the table shows that the drop in inflation under a negative shock is 152 (187) basis points, compared to corresponding lower increase of 133 (174) basis points under a positive shock. The same behaviour is observed for the output gap in both economies. On the other hand, the drop in the real interest rate is lower under a negative shock compared to the corresponding increase due to a positive shock. This asymmetry observed in real interest rates causes the asymmetry in expected real wages, as discussed above. Consequently, it creates an asymmetry in the expected cost of production, resulting in a deflation bias in the steady state. As seen in the table, since the asymmetry in the real interest rate is larger in the cost channel economy, a large deflation bias is observed in the cost channel economy compared to the no-cost channel economy.

[21]The absolute maximum change is the maximum deviation (in absolute terms) of each variable between following two states of the economy: the risky steady state and liquidity-trapped recession.

Table 5.2: Absolute Maximum Change in Variables for Positive and Negative Shocks under the CTTR

Shock Type	Absolute Maximum Change During the Shock period					
	Inflation (in basis points)		Output gap (in percentage points)		Real Int. Rate (in percent. points)	
	J=0	J=1	J=0	J=1	J=0	J=1
Negative Shock	152	187	1.07	1.13	1.4	0.8
Positive Shock	133	174	0.84	0.81	4.0	4.1

Main Results Observed for the CTTR

The following major results are obtained under the CTTR. First, when there is no ZLB constraint, the dynamic paths of variables due to a negative demand shock are almost identical under uncertainty and no-uncertainty. This result is true irrespective of the cost channel. Second, the probability of hitting the ZLB in cost channel economies is larger and more persistent under uncertainty, compared to that in no-cost channel economies. Third, the risky steady state of a cost channel economy is different (more deflation bias) from the risky steady state of a no-cost channel economy. Finally, the welfare loss is higher when uncertainty is high and the welfare loss is significantly higher in cost channel economies.

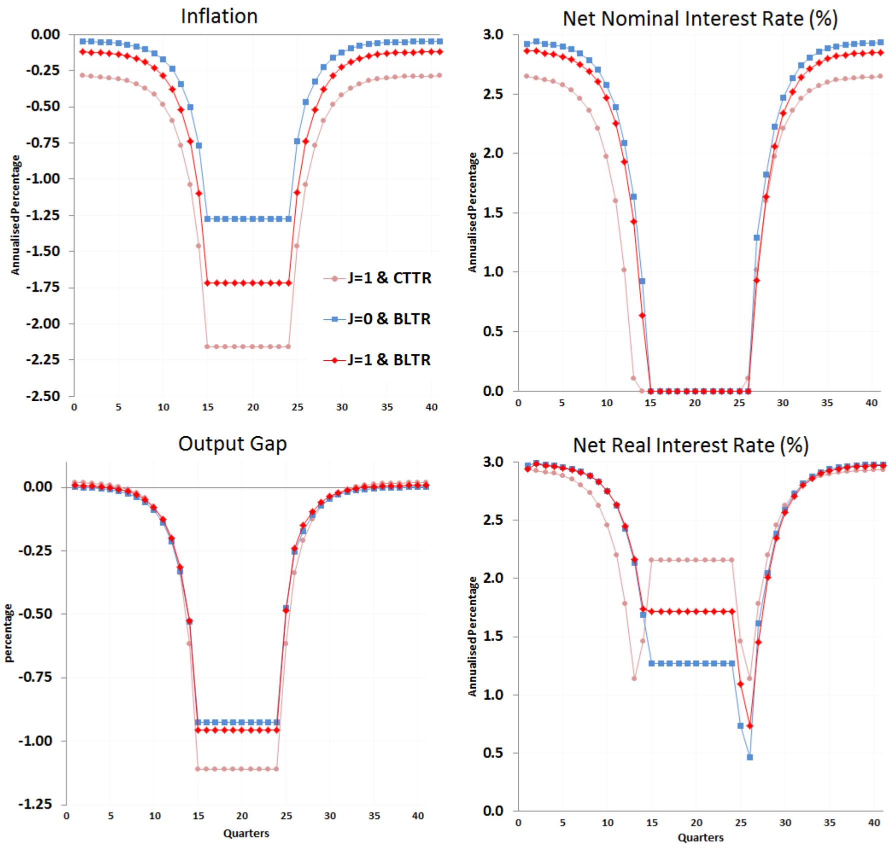
5.3.2 Alternative Interest Rules

In this section, I consider three variations of the TTR defined in Section 3.2.1 to examine the robustness of results found under the CTTR. First, I consider the backward-looking truncated rule.

Backward-looking Truncated Taylor Rule

Figure 5.9 depicts the dynamic paths of variables under the BLTR for both cost and no-cost channel economies (red line with diamonds and blue line with squares, respectively). For comparison purposes, paths of variables under the CTTR in a cost channel economy are also depicted (pink line with circles). The figure shows that under the BLTR, the wedge between the risky steady state and the deterministic steady state is less, irrespective of the cost channel, compared to under the CTTR. However, the main results found under CTTR is confirmed under the BLTR.

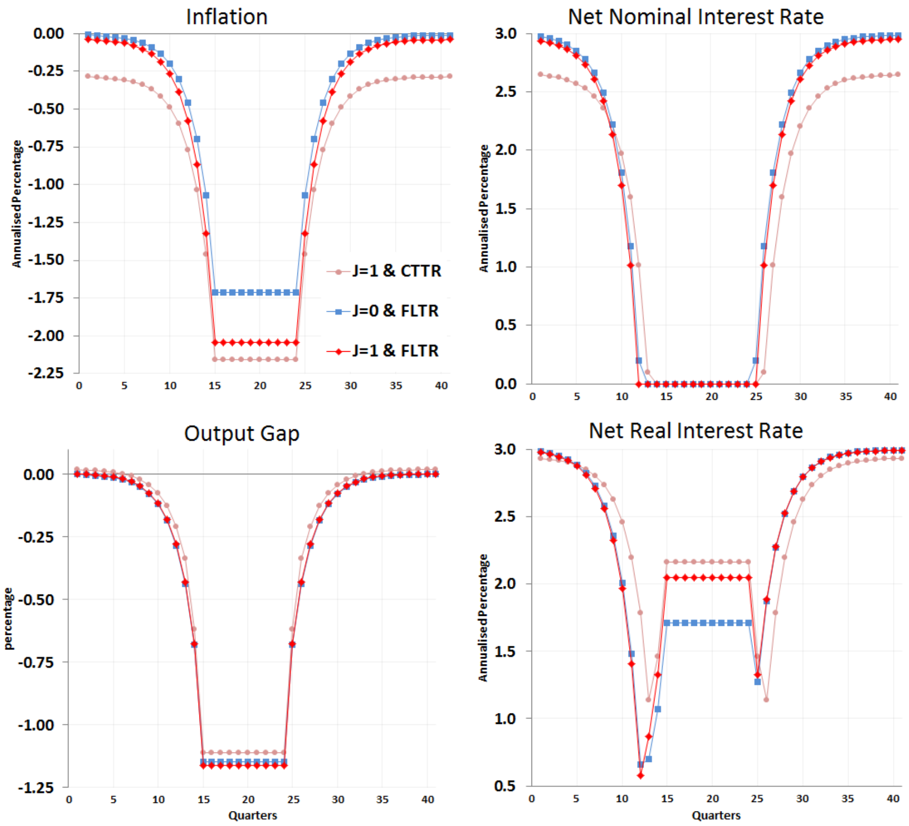
Figure 5.9: Paths of Variables under BLTR



Forward-looking Truncated Taylor Rule

Figure 5.10 depicts the dynamic paths of variables under the FLTR. The figure shows that under the FLTR, the wedge between the risky steady state and the deterministic steady state is even lower (compared to the BLTR), irrespective of the cost channel, compared to under the BLTR.

Figure 5.10: Paths of Variables under FLTR

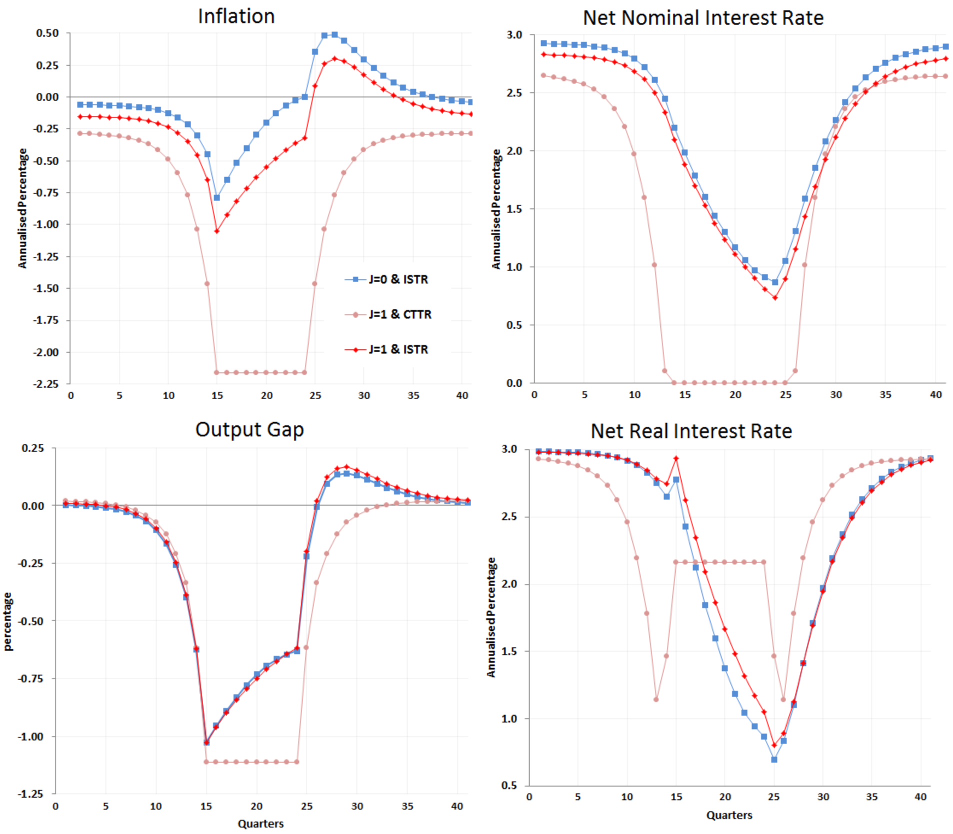


Interest Rate Smoothing Truncated Rule

Figure 5.11 depicts the dynamic paths of variables under the ISTR. In addition to the baseline calibration, the interest rate smoothing coefficient (ϕ_i) has been set at 0.9. The figure shows that nominal interest rates do not reach the ZLB under both cost and no-cost channel economies under the ISTR. This is due to the nominal interest rate smoothing.

Under ISTR, the cost channel economy is more deflationary in the liquidity trap and more deflation bias at the steady state than in the other two alternative analyses above and the CTTR.

Figure 5.11: Paths of Variables under ISTR



The macroeconomic performances for the alternative rules discussed above and the CTTR are given in Table 5.3.

Table 5.3: Macroeconomic Performances under Alternative Interest Rules

	Int. Rate Rule	Pr.of int. rates binding at ZLB (%)	Lowest Value			Risky Steady State Val.			Std. Dev.			Wel-fare Loss[1/]
			Net Nom. int Rate	Infl.	Output Gap	Net Nom. Int. Rate	infl.	Output Gap	Int. Rate	Infl.	Output Gap	
J=0	CTTR	5.9	0.00	-1.59	-1.07	2.87	-0.08	0.00	1.706	0.453	0.290	0.0156
	BLTR	3.8	0.00	-1.27	-0.92	2.92	-0.05	0.00	1.569	0.364	0.276	x 0.58
	FLTR	9.1	0.00	-1.71	-1.15	2.99	-0.01	0.00	2.031	0.544	0.349	x 0.97
	ISTR	0	0.87	-0.79	-1.03	2.93	-0.07	0.00	0.470	0.292	0.340	x 0.24
J=1	CTTR	9.9	0.00	-2.16	-1.11	2.60	-0.29	0.01	1.810	0.590	0.290	0.0600
	BLTR	6.1	0.00	-1.72	-0.96	2.82	-0.12	0.00	1.683	0.490	0.271	x 0.36
	FLTR	10.9	0.00	-2.04	-1.16	2.94	-0.04	0.00	2.137	0.656	0.347	x 0.38
	ISTR	0	0.74	-1.05	-1.03	2.83	-0.16	0.01	0.489	0.321	0.342	x 0.21

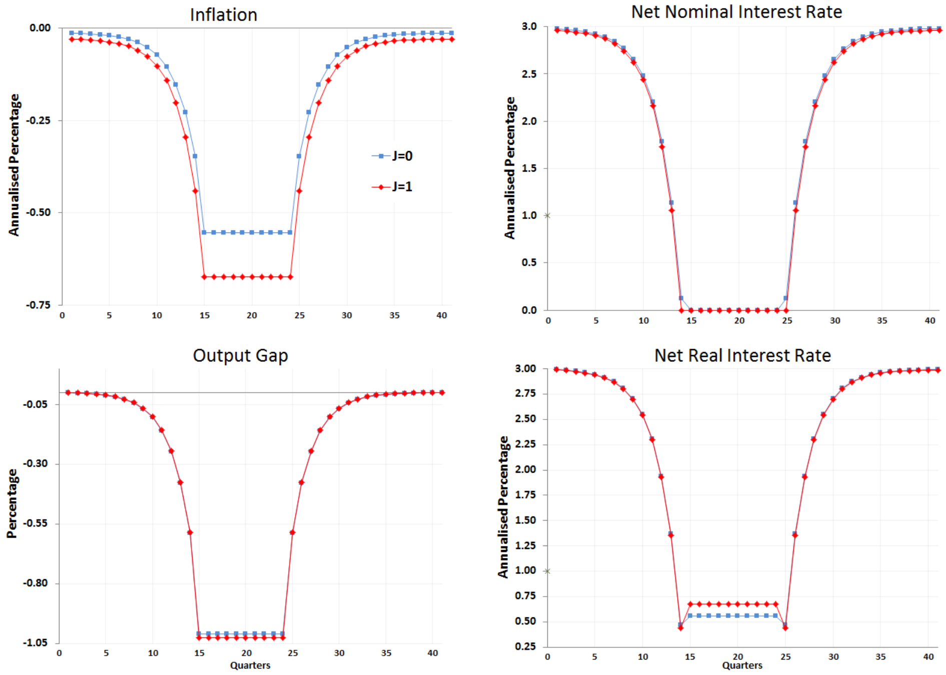
1/ Relative to baseline CTTR welfare value.

The alternative interest rate rule analysis shows the main results found under the CTTR are robust under the alternatives rules considered.

5.3.3 Alternative Calibration with a Lower Value of Slope of NKPC

I consider the robustness of results for a smaller value of the slope coefficient in a reduced-form way, to match the empirical findings of the slope of the NKPC. First, I consider the slope of the NKPC $= 0.05$ (baseline value of the slope of the NKPC $= 0.14$). Figure 5.12 shows the results. The figure confirms the results found under baseline calibration.

Figure 5.12: Paths of Variables under CTTR - With Lower Slope of NKPC (Slope$= 0.05$)



Note: Slope of the NKPC = 0.05. Baseline calibration for other parametrs.

Further, I consider a range of values for the slope of the NKPC and the standard deviation of the natural interest rate shock to confirm the above results. The results are shown in Table 5.4., which confirms the main findings of the baseline analysis.

Table 5.4: Sensitivity Analysis - Slope of the NKPC and Standard Deviation of Shock

Scenario			Pr.of int. rates binding at ZLB (%)	Lowest Value			Risky Steady State Values		
	Slope of NKPC	Std Dev. of Shock		Net Nom. int Rate	Inflation	Output Gap	Net Nom. int Rate	Inflation	Output Gap
J=0	0.024	0.75	1.52	0.00	-0.27	-1.01	2.98	-0.008	0.00
		0.90	3.94	0.00	-0.30	-1.02	2.94	-0.034	0.00
		1.00	6.07	0.00	-0.32	-1.03	2.90	-0.052	0.00
	0.05	0.75	2.26	0.00	-0.55	-1.01	2.97	-0.014	0.00
		0.90	5.37	0.00	-0.60	-1.03	2.91	-0.048	0.00
		1.00	8.39	0.00	-0.69	-1.05	2.80	-0.120	0.00
	0.1	0.75	4.22	0.00	-1.14	-1.04	2.91	-0.054	0.00
		0.90	9.31	0.00	-1.31	-1.08	2.73	-0.171	0.00
		1.00	14.48	0.00	-1.53	-1.13	2.45	-0.347	-0.01
	Baseline (0.129)	0.75	5.92	0.00	-1.59	0.00	2.87	-0.077	0.00
		0.90	14.01	0.00	-1.99	-1.14	2.43	-0.365	-0.01
J=1	0.024	0.75	1.66	0.00	-0.32	-1.01	3.00	-0.006	0.00
		0.90	4.33	0.00	-0.36	-1.02	2.90	-0.053	-0.01
		1.00	6.64	0.00	-0.40	-1.04	2.86	-0.086	0.00
	0.05	0.75	2.71	0.00	-0.67	-0.77	2.95	-0.030	0.00
		0.90	6.50	0.00	-0.77	-1.04	2.83	-0.109	0.00
		1.00	10.56	0.00	-0.93	-1.07	2.62	-0.262	0.00
	0.1	0.75	5.62	0.00	-1.41	-1.06	2.87	-0.091	0.00
		0.90	15.11	0.00	-1.90	-1.13	2.30	-0.510	0.02
		1.00	15.91	0.00	-1.74	-1.14	2.48	-0.336	0.00
	Baseline (0.129)	0.75	9.86	0.00	-2.16	-1.11	2.60	-0.291	0.01
		0.90	15.86	0.00	-2.30	-1.16	2.53	-0.326	0.00

5.3.4 Sensitivity Analysis

The sensitivity analysis under the CTTR with a large negative shock to the natural interest rates confirms the above results to various values of parameters as shown in Table 5.5.

Table 5.5: Sensitivity Analysis under CTTR

	Scenario[1/]		Pr.of int. rates binding at ZLB (%)	Lowest Value: Net Nom. int Rate	Lowest Value: Inflation	Lowest Value: Output Gap	Risky Steady State Values: Net Nom. int Rate	Risky Steady State Values: Inflation	Risky Steady State Values: Output Gap	Wel-fare Loss[2/]
J=0	Baseline		5.92	0.00	-1.59	-1.07	2.87	-0.077	0.00	0.016
	Deterministic		0.00	0.00	-1.39	-0.99	3.00	0.000	0.00	X 0.61
	Sigma	3	9.25	0.00	-1.75	-1.41	2.70	-0.187	-0.01	X 1.96
		6.25[3/]	2.97	0.00	-1.53	-0.71	2.95	-0.029	0.00	X 0.79
	Shock to Natural Interest rate	Std. dev.[4/]= 2	0.57	0.00	-1.43	-1.02	2.99	-0.004	0.00	X 0.65
		Std. dev.[4/]= 3.5	12.21	0.00	-1.90	-1.13	2.54	-0.296	0.00	X 3.54
		pho = 0.5	1.03	0.00	-0.80	-0.75	2.99	-0.007	0.00	X 0.17
		pho = 0.7	11.11	0.00	-2.34	-1.31	2.61	-0.244	-0.01	X 3.65
	Taylor Rule	phi(x)=0	0.19	0.00	-2.03	-1.30	3.00	-0.001	0.00	X 1.37
		phi(x)=0.5	2.44	0.00	-1.70	-1.13	2.97	-0.020	0.00	X 0.95
		phi(pi)=10	17.71	0.00	-1.19	-0.91	2.62	-0.033	-0.01	X 0.46
J=1	Baseline		9.86	0.00	-2.16	-1.11	2.60	-0.291	0.01	0.060
	Deterministic		0.00	0.00	-1.71	-1.09	3.00	0.000	0.00	X 0.25
	Sigma	3	15.00	0.00	-2.47	-1.51	2.34	-0.478	0.01	X 2.10
		6.25[3/]	4.58	0.00	-1.87	-0.72	2.90	-0.067	0.00	X 0.34
	Shock to Natural Interest rate	Std. dev.[4/]= 2	1.04	0.00	-1.77	-1.03	2.98	-0.013	0.00	X 0.27
		Std. dev.[4/]= 3.5	15.46	0.00	-2.33	-1.16	2.48	-0.365	0.01	X 1.41
		pho = 0.5	1.49	0.00	-1.00	-0.76	2.97	-0.023	0.00	X 0.07
		pho = 0.7	16.66	0.00	-2.40	-1.40	2.36	-0.452	0.01	X 2.38
	Taylor Rule	phi(x)=0	0.41	0.00	-2.25	-1.30	3.00	0.000	0.00	X 0.44
		phi(x)=0.5	3.87	0.00	-2.03	-1.15	2.92	-0.056	0.00	X 0.38
		phi(pi)=10	27.69	0.00	-1.56	-0.91	2.05	-0.090	-0.01	X 0.26

1/ For each scenario, I change one parameter value leaving other parameter values at baseline level.
2/ Relative to baseline welfare value.
3/ Value used by Woodford (2003).
4/ Values are in annual terms.

5.4 Forward Guidance Rule

This section considers the FG rule as described in Section 3.2.2. Recall, the rule specifies that the monetary authority promises to delay exiting the zero interest rate policy following a liquidity-trapped recession until the lagged output gap returns to a specific level given by the parameter a. Further, it is assumed, whenever the ZLB is not binding, the central bank follows the baseline Taylor rule: the CTTR.

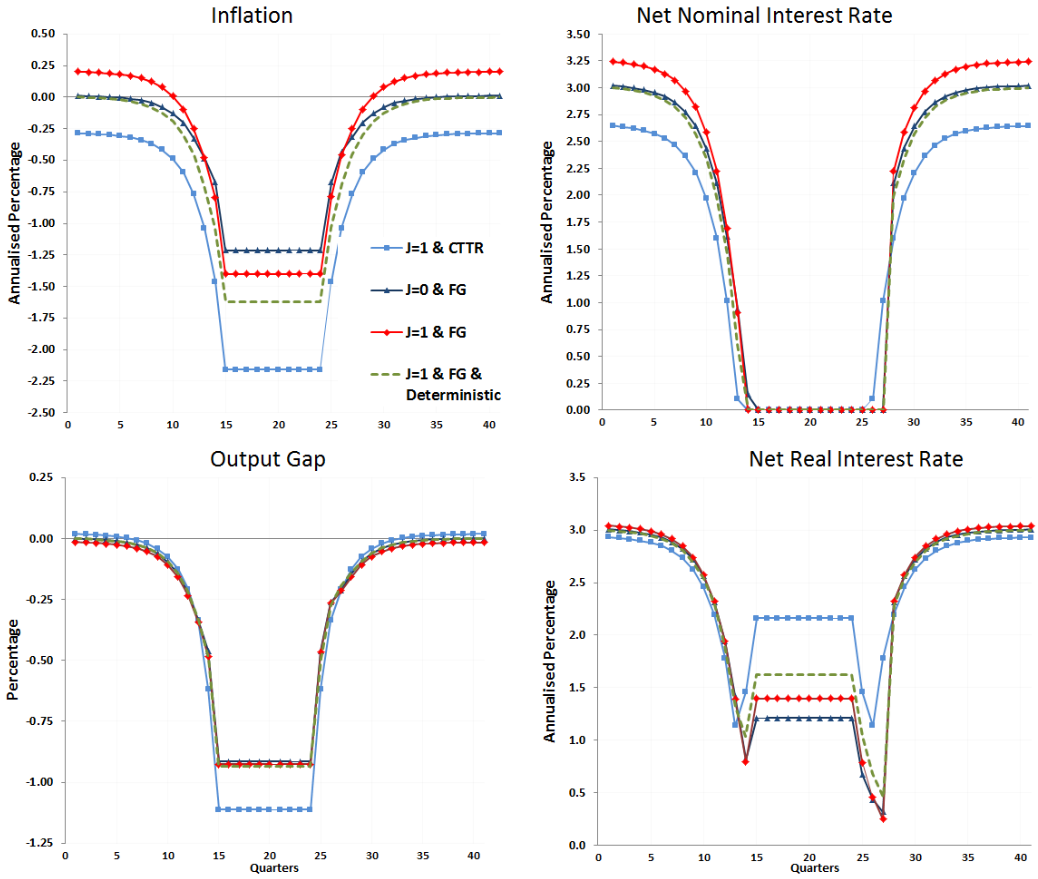
First, I simulate the model with a baseline calibration and then move to sensitivity analysis.

5.4.1 Baseline Simulation

Figure 5.13 depicts paths of variables under forward guidance. Recall in the baseline case: $a = -0.25$. For comparison purposes, four different specifications are depicted as follows: (a) the stochastic cost channel economy under the CTTR (light blue line with squares), (b) The FG rule in a stochastic no-cost channel economy (dark blue line with triangles), (c) The FG rule in a stochastic cost channel economy (red line with diamonds) and (d) The FG rule in a deterministic cost channel economy (green dashed line).

The top right panel of Figure 5.13 depicts paths of nominal interest rates. Under forward guidance, the central bank holds interest rates at the zero level for longer – an additional 2 quarters – both under cost channel and no-cost channel economies, compared to the CTTR case.

Figure 5.13: Paths of Variables under Forward Guidance



Note: Forward guidance: a=-0.25.

The top left panel of Figure 5.13 shows the dynamic paths of inflation. It is immediately clear that under forward guidance, there is no deflation bias in the steady state; rather, *the inflation bias* is evident, especially in cost channel economies.[22] Table 5.6 shows that the inflation bias is observed only when the central bank carries out strict forward guidance, while the deflation bias is observed when

[22]Table 5.6 gives quantitative values for the inflation bias. When $a = -0.25$ – baseline value – the inflation bias for the no-cost channel economy is marginal with 1 basis point while the inflation bias for the cost channel economy is significantly high with 21 basis points.

the central bank carries out weak forward guidance.[23] Accordingly, by announcing an appropriate FG rule, the central bank can achieve its inflation target. According to the analysis, the appropriate approximate value for the no-cost channel economy is $a = -0.30$ while for the cost channel economy it is $a = -0.45$.

The observation of higher risky steady state inflation under the FG rule is due to two distinct and opposite effects. The first occurs irrespective of the forward guidance, as explained in Section 5.3.1 under the CTTR. When the economy is hit with a large negative shock; the ZLB binds; therefore, the additional decline in the real wage will not be contained, which is not observed under a positive shock. This asymmetry of real wages lowers expected real wages and thereby the expected cost of production, which in turn reduces steady state inflation.

The second effect is explicitly due to the FG rule. Under forward guidance, the central bank promises to keep zero interest rates longer following a liquidity-trap. This announcement revises private sector inflationary expectations upwards and thereby increases actual inflation during a liquidity trap. Consequently, it reduces expected real interest rates, and thereby increasing expected real wages.[24] This effect does not prevail in the case of a corresponding large positive shock. Accordingly, it creates an asymmetry in the expected production cost in the opposite direction to the first effect.[25] This results in higher inflation in the risky steady state.

The net impact of the above two distinct effects determines the steady state inflation under forward guidance. If the first effect is dominant, the deflation bias is observed in the steady state. If the second effect is dominant, i.e. when the strict forward guidance is carried out, the inflation bias is observed. The cost channel amplifies the above effects, as the cost channel makes the ZLB more frequent.

The bottom left panel of Figure 5.13 shows that the recession is milder under forward guidance, irrespective of the cost channel. This is because the central bank can manage the expectations of the private sector under forward guidance and increase inflation expectations to stimulate the economy.

The macroeconomic performances under different specifications of the FG rule and under the CTTR are given in Table 5.6. The table shows that, whenever the central bank carries out a very weak forward guidance (for example, $a = -10$), the results converge to the CTTR specification. The table confirms that the depth of the recession is improved with the FG rule, compared to the

[23] I consider $a >= -0.5$ as strict forward guidance.

[24] The argument for additional increase in expected real wages at the ZLB under the FG rule is analogous to the CTTR given in Footnote 62.

[25] This asymmetry is further elaborated under the positive shock analysis under the FG rule later in this section.

CTTR policy. For example, in the recession, the lowest value of the output gap for forward guidance when $a = -0.25$ is -0.93, compared to the value of -1.11 reported under the CTTR in cost channel economies. The table shows that the welfare loss is also reduced significantly under strict forward guidance, irrespective of the cost channel, compared to under the CTTR.

Table 5.6: Macroeconomic Performances under Forward Guidance

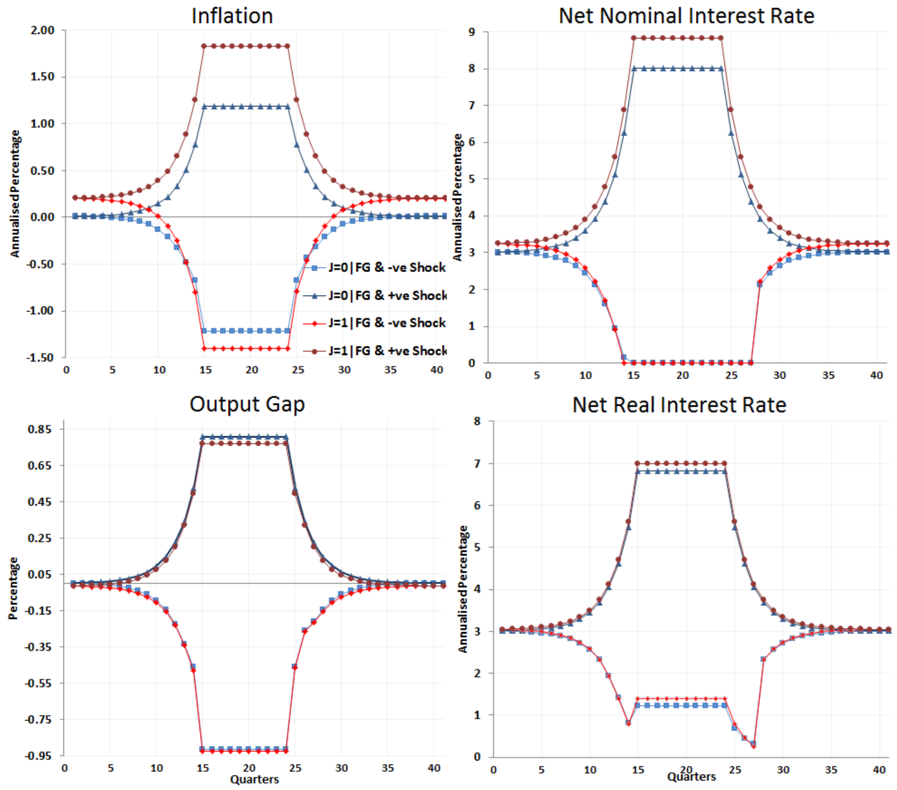
Measure	J=0						J=1					
	CTTR	Value of FG Parameter: a					CTTR	Value of FG Parameter: a				
		-0.25	-0.5	-0.75	-1	-10		-0.25	-0.5	-0.75	-1	-10
% of time nominal Interest rate bounded by Zero[1/]	5.92	2.29	4.56	5.76	5.91	5.92	9.86	3.06	7.76	9.52	9.83	9.86
Additional periods i binding	0	3	2	1	1	1	0	3	2	1	1	1
Lowest value (%):												
Net Nom. Interest Rate	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Inflation	-1.59	-1.21	-1.37	-1.54	-1.57	-1.59	-2.16	-1.40	-1.91	-2.11	-2.14	-2.16
Output Gap	-1.07	-0.91	-0.98	-1.04	-1.05	-1.07	-1.11	-0.93	-1.03	-1.09	-1.09	-1.11
Steady state value (%) of:												
Net Nom. Interest Rate	2.87	3.04	3.02	2.90	2.88	2.87	2.60	3.27	2.81	2.64	2.60	2.60
Inflation	-0.08	0.01	0.01	-0.06	-0.08	-0.08	-0.29	0.21	-0.14	-0.26	-0.29	-0.29
Output Gap	-0.003	0.005	-0.001	-0.002	-0.003	-0.003	0.009	-0.009	0.005	0.008	0.009	0.009
Standard Deviation[1/] of:												
Net Nom. Interest Rate	1.706	x 0.93	x 0.99	x 1.00	x 1.00	x 1.00	1.810	x 0.98	x 1.00	x 1.00	x 1.00	x 1.00
Inflation	0.453	x 0.85	x 0.96	x 0.99	x 1.00	x 1.00	0.590	x 0.90	x 0.97	x 0.99	x 1.00	x 1.00
Output Gap	0.290	x 0.91	x 0.97	x 0.99	x 1.00	x 1.00	0.290	x 0.89	x 0.96	x 0.99	x 1.00	x 1.00
Welfare Loss[1/]	0.0156	x 0.46	x 0.59	x 0.89	x 0.97	x 1.00	0.0600	x 0.41	x 0.47	x 0.88	x 1.00	x 1.01

1/ Relative to the value of CTTR.

Analysis with a Large Positive Shock to the Economy

Paths of variables under the FG rule due to a corresponding positive shock are considered in this section. Paths are given in the Figure 5.14.

Figure 5.14: Paths of Variables to a Large Positive Shock to the Economy under Forward Guidance



Note: Path of the natural interest rate to a positive shock is symmetric to the negative shock. Accordingly, the maximum value of the net natural interest rate duirng the liquidity trap is 12%.

To illustrate the asymmetry in quantitative terms, I tabulate values in Table 5.7. The table gives the absolute change in inflation and the output gap under both negative and positive shocks as well as cost and no-cost channel economies under forward guidance.[26] In contrast to the finding under the CTTR, Figure 5.14 and corresponding Table 5.7, show that under the FG rule, the asymmetry between negative and positive shocks has been reduced. In particular, the drop in the real interest rate in a negative shock is larger. Under the FG rule, the additional drop in real interest rates increases expected real wages compared to under the CTTR, affecting the asymmetry in expected production costs. These results are valid for both cost and no-cost channel economies, but magnitudes are larger for the cost channel economy.

[26]The absolute maximum change is the maximum deviation (in absolute terms) of each variable between following two states of the economy: the risky steady state and liquidity-trapped recession.

Table 5.7: Absolute Maximum Change in Variables for Positive and Negative Shocks under FG

Shock Type	Absolute Maximum Change During the Shock period					
	Inflation (in basis points)		Output gap (in percentage points)		Real Int. Rate (in percent. points)	
	J=0	J=1	J=0	J=1	J=0	J=1
Negative Shock	122	160	0.91	0.91	1.8	1.6
Positive Shock	117	162	0.81	0.79	3.8	4.0

Note: Forward Guidance: a=-0.25

Main Results Observed for the Forward Guidance Rule

Irrespective of the cost channel, the following results are obtained under the FG rule. First, the deflation bias observed under TTR policies can be avoided using the FG rule. Further, strict forward guidance generates an inflation bias in the risky steady state. Second, forward guidance reduces the probability of hitting the ZLB compared to under the CTTR policy. Third, recessions under the FG rule are less painful than under the CTTR.

The cost channel increases the inflation bias of forward guidance.

5.4.2 Sensitivity Analysis

The sensitivity analysis for the FG rule when $a = -0.25$ is given in Table 5.8. This analysis confirms the robustness of the findings of the above section.

Table 5.8: Sensitivity Analysis under Forward Guidance

	Scenario[1/]		Pr.of int. rates binding at ZLB (%)	Additional Periods int.rate binding[2/]	Lowest Value			Risky Steady State Val.			Welfare Loss[3/]
					Net nom. Int. Rate (%)	Infl.	Output Gap	Net Nom. Int. Rate (%)	Infl.	Output Gap	
J=0	Baseline FG[4/]		2.29	3	0.00	-1.21	-0.91	3.04	0.01	0.005	0.007
	Deterministic		0.00	3	0.00	-1.24	-0.90	3.00	0.00	0.00	X 0.98
	Sigma	6	1.21	2	0.00	-1.22	-0.62	3.12	0.08	0.00	X 1.31
	Shock to Natural Interest rate	std. dev.[5/]= 2	0.17	3	0.00	-1.21	-0.91	3.02	0.01	0.00	X 1.01
		pho = 0.6	1.13	2	0.00	-0.83	-0.76	3.14	0.09	0.00	X 0.82
	Taylor Rule	phi(x)=0.5	0.57	3	0.00	-1.30	-0.95	3.05	0.03	0.00	X 1.20
		phi(pi)=10	15.77	2	0.00	-1.07	-0.85	2.77	-0.02	-0.01	X 0.77
	Slope of NKPC	0.024	0.47	3	0.00	-0.22	-0.85	2.99	-0.01	0.00	X 0.06
		0.05	0.66	3	0.00	-0.38	-0.86	3.10	0.06	0.00	X 0.30
		0.1	1.14	3	0.00	-0.76	-0.88	3.18	0.13	0.00	X 1.18
J=1	Baseline FG[4/]		3.06	3	0.00	-1.40	-0.93	3.27	0.21	-0.009	0.025
	Deterministic		0.00	3	0.00	-1.62	-0.93	3.00	0.00	0.00	X 0.55
	Sigma	6	2.90	2	0.00	-1.71	-0.65	2.92	-0.07	0.01	X 0.73
	Shock to Natural Interest rate	Std. dev.[5/]= 2	0.40	3	0.00	-1.58	-0.94	3.04	0.03	0.00	X 0.52
		Std. dev.[6/7/]= 3.1	3.55	3	0.00	-1.35	-0.92	3.35	0.27	-0.01	X 1.41
		pho = 0.5[6/]	0.52	2	0.00	-0.78	-0.64	3.13	0.10	0.00	X 0.25
		pho = 0.6	2.37	2	0.00	-1.30	-0.80	2.96	-0.05	0.01	X 0.37
		pho = 0.7[6/]	5.72	3	0.00	-1.98	-1.13	3.23	0.17	-0.01	X 1.26
	Taylor Rule	phi(x)=0.5	1.11	3	0.00	-1.41	-0.95	3.40	0.29	-0.02	X 1.68
		phi(pi)=10	26.74	3	0.00	-1.48	-0.87	2.18	-0.08	-0.01	X 0.56
	Slope of NKPC	0.024	0.55	3	0.00	-0.28	-0.86	3.00	-0.01	0.00	X 0.09
		0.05	0.88	3	0.00	-0.41	-0.86	3.22	0.16	0.00	X 1.39
		0.1	2.53	3	0.00	-1.16	-0.92	3.01	-0.01	0.01	X 0.99

1/ For each scenario, I change one parameter value leaving other parameter values at baseline level.

2/ Number of additional periods R=1 when the natural interest rates is recovering following the liquidity trap.

3/ Relative to a=-0.25 welfare value.

4/ Baseline Forward guidance: a=-0.25.

5/ Values are in annual terms.

6/ It is not possible to compute an equilibrium under this scenrio when J=0 case.

6 Conclusion

The main aim of this study was to examine the behaviour of the main macroeconomic variables under interest rate rules in a cost channel economy in the presence of the ZLB. The ZLB is considered as an occasionally binding constraint. In addition to this, an endogenous threshold-based forward guidance rule was examined.

The study revealed some important results for the conducting of monetary policy in a cost channel economy at the ZLB under a TTR. First, the probability of hitting the ZLB is larger in cost channel economies under uncertainty compared to that of no-cost channel economies. This is because, during the shock period when the central bank cuts interest rates, the marginal cost of production drops more in cost channel economies than in no-cost channel economies, resulting in a larger drop in inflation. This result shows that the cost channel economy is more likely to fall into a liquidity-trapped recession. Further, cost channel economies remain longer in the liquidity trap than no-cost channel economies. Second, the risky steady state of a cost channel economy is different (more deflation bias) from the risky steady state of a no-cost channel economy. The reason for that is the amplified asymmetry of the expected cost of production created by the ZLB constraint in cost channel economies. The study also revealed that the welfare loss is higher when uncertainty is high and the welfare loss is significantly higher in cost channel economies compared to in no-cost channel economies. The above results suggest that achieving the inflation target in cost channel economies is more challenging than in no-cost channel economies, if agents expect future liquidity traps.

According to the FG rule, the monetary authority promises to keep interest rates at the ZLB following a liquidity trap until the lag of the output gap recovers up to a pre-determined and pre-announced value. The monetary authority announces the FG rule at time zero. Under the FG rule, the following results hold, irrespective of the cost channel: First, by announcing an appropriate FG rule, the deflation bias observed under the TTR policy can be avoided. In addition, strict forward guidance leads to an inflation bias in the risky steady state. This happens because of the following: since the monetary authority promises to keep interest rates at the ZLB longer, the private sector revises inflation expectations upward. Consequently, the asymmetry of expected production costs causes agents to expect higher production costs during the ZLB policy period. This makes current prices higher, resulting in a higher inflation at the steady state. Second, forward guidance reduces the probability of hitting the ZLB compared to the TTR policy. Third, the depth of the recession under the FG rule is less painful and welfare maximising than under the TTR policy. The cost channel amplifies the increase in inflation at the risky steady state under the FG rule.

The findings of this study suggest that if a cost channel is present in an economy, the transmission of monetary policy may be different from that in a no-cost channel economy in the presence of the ZLB. Additionally, if agents expect future recessions, achieving the inflation target is more challenging in cost channel economies. Therefore, central banks should pay careful attention to the cost channel of monetary policy when they set policies under such economic conditions. Further, this study finds that the endogenous FG rule improves welfare compared to interest rules considered.

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