Term Structure Dynamics in India: A DSGE Analysis

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Abstract

This paper develops and estimates a macro-finance model. In particular, using the preferred habitat approach, we integrate the behaviour of the term structure of interest rates within a New Keynesian DSGE model. We assume market segmentation by introducing bonds with different maturity periods. We further assume imperfect substitutability among assets due to the presence of an investment adjustment cost. Using the Bayesian estimation technique, the model is estimated for the Indian economy over the period 2000Q1-2020Q4. Results show that the model is consistent with the actual yield curve behaviour and generates a volatile term premium. Therefore, the framework in this paper shows the possibility to analyse the term structure behaviour in a micro-founded structural macroeconomic model.

Keywords: Macro-Finance; New-Keynesian; term-structure; yields; Bayesian Estimation; preferred-habitat; Indian economy.

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1 Introduction

The term structure of interest rate or the yield curve is an important indicator of the macroeconomy. But, macroeconomic models, when embedded with term structure dynamics, are unable to produce sufficiently large and volatile term premium[1]. These models produce volatile term-premium but at the cost of distorting the model fit of macro data. Since dynamic stochastic general equilibrium (DSGE) models are structural models which use general equilibrium framework, they are the best available methods to see how macroeconomic fundamentals affect the term-premium. But, these models have been failed to generate volatile term-premium. In Macro-Finance literature, this inability of DSGE models is termed as "Bond-premium puzzle" (Rudebusch, Swanson, & Wu, 2006; Rudebusch & Williams, 2009). A great amount of literature has emerged in an effort to solve this puzzle (Rudebusch & Swanson, 2008; Hördahl et al., 2008; Rudebusch & Swanson, 2012; Falagiarda & Marzo, 2012; Kaszab & Marsal, 2015). There are various approaches which try to find the solution of this puzzle.

One approach is to use higher-order approximations along with habit formation in household's consumption and labour market frictions (Campbell & Cochrane, 1999; Rudebusch, Sack, & Swanson, 2006; Rudebusch & Swanson, 2008; Rudebusch & Williams, 2009). These models have been somewhat able to find a larger and volatile term premium, but the term premium is not comparable to the data. This volatile term premium is achieved at the cost of model's fit to the macroeconomic data. These models use third and

[1] Term-premium is the difference between interest rate of long-term maturity and short-term maturity.

higher-order approximations to achieve this volatility in term premium.

The second approach replaces log-utility preferences with recursive preferences or Epstein & Zin (1991) preferences. In this type of utility function, inter-temporal elasticity of substitution is differentiated from the inverse of the coefficient of risk-aversion. Using the recursive preferences within a DSGE framework, Rudebusch & Swanson (2012); Van Binsbergen et al. (2012); Kaszab & Marsal (2015); Marsal et al. (2016) are able to generate sufficiently large volatility of term premium. Again, this volatility comes at the cost of very high value of the coefficient of risk aversion parameter. Christoffel et al. (2010); Nguyen (2018); Bretscher et al. (2020) are some noteworthy contributions in exploring Epstein-Zin preferences.

Another approach incorporates heterogeneous agents within DSGE models (De Graeve et al., 2010; Guvenen, 2009; Bretscher et al., 2019). These models are termed as HANK (Heterogeneous agents New-Keynesian) models. This approach is relatively less explored. De Graeve et al. (2010); Bretscher et al. (2019) in their models assume heterogeneity in households and producers. They are able to generate term premium comparable to the real data. (Rudebusch, Swanson, & Wu, 2006)

Higher-order approximation and recursive preferences are usually complex and demand high computational techniques. Falagiarda & Marzo (2012), Suo & Tanaka (2018) and Costa (2019) use an alternative approach, which is relatively easy to handle and saves a lot of computational burden. They use the theory of preferred habitat and observe that this approach is also able to produce similar term premium behaviour, which is comparable to the studies with higher-order approximations. Most studies concerning the term-premium behaviour within DSGE models are conducted for developed economies in European Union and the US, with very few such studies for developing economies. To the best of our knowledge, in the Indian context, there is no such study that explores the term-premium changes due to policy shocks in a general equilibrium environment.

The present study adopts the framework from Falagiarda & Marzo (2012) and Costa (2019) to analyse the term-premium behaviour in an estimated New-Keynesian DSGE model for the Indian economy. The proposed model is different from standard Smets & Wouters (2007) DSGE model in the sense that it assumes imperfect substitutability between assets (bonds of different maturities in our model). We assume the market segmentation hypothesis where the financial market is characterised by different segments wherein each segment has different bond maturities. Estimation results show that the model is consistent with the term-premium behaviour, and it is also comparable with the macroeconomic data for Indian economy.

Preferred Habitat Theory

Introduced by Modigliani & Sutch (1966), the preferred-habitat theory states that investors prefer to invest in particular maturity segments (habitat) and they will choose other maturities only if given a premium. Whenever there is a mismatch between supply and demand for bonds of a particular maturity, investors will tend to invest outside their preferred maturities to take advantage of any mismatch. But, it will require a higher yield to cover for the risk associated with investing in maturities outside their preferred habitat.

This extra yield necessary to induce investors to come out of their habitats is called the risk premium. Thus, according to this theory, the shape of the yield curve depends on future expected rates and a risk premium. This risk premium can be negative or positive depending on the demand and supply imbalance at various maturities. Therefore, all shapes of the yield curve, upward, downward or flat, are possible (Kariuki & KITATI, 2016).

Preferred habitat has been observed worldwide during different market episodes. The US Treasury 2002 buyback program is one such example when Treasury announced to buy back long-term bonds. Three weeks after the announcements, yields on 30-year maturity bonds fell by 58-60 basis points, resulting in a price increase of around 10 per cent. But, this effect was limited to long-term maturity only. Yields on 2 to 5-year maturity fell only by 9 basis points. Another example is U.K. pension reforms. As part of the reforms, pension funds were asked to assess their pension liabilities using long-term bond returns. Therefore, pension funds acquired considerable amounts of long-term bonds to protect themselves against prospective decreases in long-term interest rates. As a result, long rates plummeted to record low levels, widening the gap between 30-year and 10-year bond yields. Japan experienced the same during the Quantitative and Qualitative Monetary Easing (QQE) program in 2013 when the Japanese central bank purchased long-term bonds at a large scale, deriving down the yields on long-term yields. In the Indian case, preferred habitat is observed during the operation twist operation by RBI in April 2020. Under this operation, RBI sold short-term securities and purchased long-term securities simultaneously. The goal of this operation was to drive down long term rates to stimulate corporate investment. These effects are consistent with preferred habitat theory since operation twist works as a supply shock to long term bonds (Vila, 2009).

2 Model

We borrow the framework from Falagiarda & Marzo (2012) and Costa (2019). The model is a standard New Keynesian model with the inclusion of different maturity bonds. The model also features a portfolio adjustment cost to choose among different bond maturities.

2.1 Household

This block analyses household's behaviour by dividing the budget on consumption and savings. There is a continuum of representative households, $j \in [0, 1]$ who optimizes his consumption and leisure subject to the budget constraint. We assume that the household is liquidity unconstrained and has full access to the capital market. Following Fuhrer (2000), we incorporate habit formation in consumption pattern of household. Studies (Hall, 1978; Ferson & Constantinides, 1991) suggest that habit formation has influence on household behaviour.

For consumer's inter-temporal optimization problem, we can think of various utility function forms, but to have a unique solution, a concave utility function with diminishing marginal returns to consumption is more appropriate. The best solution for this class of utility functions is a constant relative risk aversion (CRRA) utility function (King et al., 1988; Clarida et al., 2000). Therefore, household maximizes the following CRRA utility function with the inclusion of habit persistence:

$$\max_{C_{j,t},L_{j,t},B_{S\,j,t+1},B_{L\,j,t+1}} E_t \sum_{t=0}^{\infty} \beta^t S_t^P \left[\frac{(C_{j,t} - \phi_c C_{j,t-1})^{1-\eta}}{1-\eta} - S_t^L \frac{L_{j,t}^{1+\omega}}{1+\omega} \right] \tag{1}$$

where β is the inter-temporal discount factor, which captures the impatience, η is the relative risk-aversion parameter, which is also reciprocal to the elasticity of substitution of consumption. ω is the marginal disutility of labour or reciprocal to the elasticity of substitution of labour supply, ϕ_c is the habit persistence parameter. S_t^P and S_t^L are the preference shocks. S_t^P affects intertemporal choices for consumption and savings and follows AR(1) process:

$$logS_t^P = \rho_P log S_{t-1}^P + \epsilon_{(P,t)} \tag{2}$$

where $\epsilon_{P,t}$ is an i.i.d. shock with $\epsilon_{P,t} \sim N(0, \sigma_P)$. S^L is the preference shock for labour supply and it also follows AR(1) process:

$$logS_t^L = \rho_L log S_{t-1}^L + \epsilon_{(L,t)} \tag{3}$$

where $\epsilon_{L,t}$ is an i.i.d. shock with $\epsilon_{L,t} \sim N(0, \sigma_L)$.

Household must respect the following budget constraint to maximize its utility in Equation (1):

$$C_{j,t}P_t + \frac{B_{S,j,t+1}}{R_{S_t}^B} + \frac{B_{L,j,t+1}}{R_{L_t}^B}(1 + AC_t^L) = W_t L_{j,t} + B_{S,j,t} + \frac{B_{L,j,t}}{\prod_{i=2}^{N_L} R_{S,t+i-1}^B} - T_{j,t} \tag{4}$$

where P is the price level, W is wage rate, L is the labour supply (number of hours worked). Household pay the lump-sum tax T. Household holds two types of zero-coupon bonds - short-term (B_S) maturity and long-term (B_L) maturity bonds. Returns on both type of maturities are R_S^B and R_L^B, respectively. The term N_L is the maturity of long-term bond.

Budget constraint in Equation (4) has distinguished features. First, It allows for bond trading in the secondary market because both maturity types of bonds - short term and long term are priced with the short-term interest rate (Ljungqvist & Sargent, 2018). As in R.H.S of (4), if the household purchases a long-term maturity bond in period t and sells it in future, he would be uncertain about the gains because short-term interest rate in future $(t + 1)$ is not known today in period t.

Another feature of the budget constraint is the introduction of portfolio-adjustment cost. Presence of this adjustment cost eliminates the possibility of arbitrage which tends to equal yields on both maturity bonds and, therefore makes it possible to segment the bond markets into different maturities. Following Falagiarda & Marzo (2012), portfolio-adjustment cost is quadric and defined as:

$$AC_t^L = \left[\frac{\vartheta_L}{2} \left(\frac{B_{L,t+1}}{B_{L,t}} \right)^2 \right] Y_t \tag{5}$$

where AC^L is the cost of adjusting the portfolio of maturity L. ϑ_L is the parameter related to the sensitivity of adjustment cost of maturity L. The rationale behind this cost comes from the preferred-habitat theory which says that investors have preferences to invest over different maturity bonds. The magnitude of ϑ_L vary across maturities because of the different opportunity costs associated with bonds at each maturity. From Equation (5), to maintain supply and demand equilibrium for a particular maturity bonds, an increase (decrease) in the supply of a bond should be accompanied by an increase (decrease) in the adjustment cost for that maturity bond.

Household maximizes his utility in (1) subject to the budget constraint (4) and (5). First order conditions [2] for the household maximization problem are:

$$\lambda_{j,t} P_t = S_t^P (C_{j,t} - \phi_c C_{j,t-1})^{-\eta} - \phi_c \beta E_t [S_{t+1}^P (C_{j,t+1} - \phi_c C_{j,t})^{-\eta}] \tag{6}$$

$$S_t^P S_t^L L_{j,t}^{\omega} = \lambda_{j,t} W_t \tag{7}$$

$$\frac{\lambda_{j,t}}{R_{S,t}^B} = \beta E_t \lambda_{j,t+1} \tag{8}$$

$$\frac{1}{R_{L,t}^B}\left[1 + \frac{3}{2}\vartheta_L \left(\frac{B_{L,t+1}}{B_{L,t}}\right)^2 Y_t\right] = E_t \left\{ \Xi_{j,t,t+1} \left[\left(\frac{1}{\prod_{i=2}^{N_L} R_{S,t+i-1}^B} \right) + \left(\frac{1}{R_{L,t+1}^B} \right) \vartheta_L \left(\frac{B_{L,j,t+2}}{B_{L,j,t+1}} \right)^3 Y_{t+1} \right. \right. \tag{9}$$

Combining of Equations (6) and (7) give the expression for labour supply. Equations (8) and (9) are the Euler equations for short-term and long-term bond. $\Xi_{j,t,t+1}$ is the stochastic discount factor (SDF), expression for SDF or pricing kernel is:

[2] First order conditions are derived in Appendix.

$$E_t \Xi_{j,t,t+1} = \beta E_t \left(\frac{\lambda_{j,t+1}}{\lambda_{j,t}} \right) \tag{10}$$

2.2 Firms

This section focuses on the firms' behaviour in the economy. There are three types of firms - intermediate goods producing, final goods producing and capital goods producing firms..

2.2.1 Final goods firms or retail firms

Final goods firms purchase intermediate goods from intermediate goods producers, integrate these goods and sell them to households in a perfectly competitive market. Firms aggregate goods following Dixit-Stiglitz aggregator function (Dixit & Stiglitz, 1977):

$$Y_t = \left(\int_0^1 Y_{j,t}^{\frac{\varphi-1}{\varphi}} dj \right)^{\frac{\varphi}{\varphi-1}} \tag{11}$$

where $Y_{j,t}$ is intermediate good and Y_t is the final good after aggregating the intermediate goods. $\varphi > 1$ is the elasticity of substitution between intermediate goods. If P_t is the general price level and $P_{j,t}$ is the price for intermediate good, then maximization problem of the retail firm is

$$\max_{Y_{j,t}} P_t Y_t - \int_0^1 P_{j,t} Y_{j,t} dj \tag{12}$$

subject to the aggregator function in Equation (11).

solving the maximization problem for retail firm, we get the demand function for intermediate good $Y_{j,t}$:

$$Y_{j,t} = Y_t \left(\frac{P_t}{P_{j,t}} \right)^{\varphi} \tag{13}$$

again substituting this expression in aggregator function Equation (11), we get the expression for aggregate price level:

$$P_t = \left(\int_0^1 P_{j,t}^{1-\varphi} dj \right)^{\frac{1}{1-\varphi}} \tag{14}$$

2.2.2 Intermediate Goods Firms

Intermediate goods firm or the wholesale firms produce differentiated intermediate goods and sell them to retail goods firms. Due to the differentiated nature of their products, they enjoy some degree of market power, therefore there is monopolistic competition in this market structure. These firms use labour and capital as inputs and follow the Cobb-Douglas production function:

$$Y_{j,t} = A_t (U_t K_{j,t})^{\alpha} L_{j,t}^{1-\alpha} \tag{15}$$

where α is the share of capital and U_t is the capacity installed. We include U_t because of the assumption of underutilisation of installed capacity which we discuss in detail in next section. A_t is the level of technology which follows AR(1) process:

$$logA_t = \rho_A logA_{t-1} + \epsilon_{A,t} \tag{16}$$

where $\epsilon_{A,t}$ is an i.i.d. shock with $\epsilon_{A,t} \sim N(0, \sigma_L)$. Intermediate firms determine inputs by minimising the production cost:

$$\min_{L_{j,t}, K_{j,t}} W_t L_{j,t} + R_t U_t K_{j,t} \tag{17}$$

subject to production function in Equation (15). Solving for first order conditions gives the demand functions for labour and capital:

$$L_{j,t} = mc_{j,t}(1-\alpha)\frac{Y_{j,t}}{W_t} \tag{18}$$

$$U_t K_{j,t} = mc_{j,t}\alpha\frac{Y_{j,t}}{R_t} \tag{19}$$

where marginal cost $mc_{j,t}$ is the Lagrange multiplier.

$$mc_{j,t} = \frac{1}{A_t}\left(\frac{W_t}{1-\alpha}\right)^{1-\alpha}\left(\frac{R_t}{\alpha}\right)^{\alpha} \tag{20}$$

2.2.2.1 Calvo Pricing

After deciding for input demands, now firm defines the prices of intermediate goods following the Calvo rule (Calvo, 1983). Under this rule, in a period, only a fraction of total firms selected are allowed to change the prices when they receive the random signal. Remaining firms define their prices following the stickiness rule, like maintaining the previous period's price or updating the price based on previous period's inflation rate. There is a θ probability that a firm keeps its price fixed in the next period and a $1-\theta$ probability that it receives the random signal and reset the price to an optimal price

$P^*_{j,t}$. For the firm which reset its prices, there is θ probability that the price remain fixed in time $t+1$ and θ^2 probability to remain fixed in $t+2$ and so on. Intermediate firms internalise these probabilities while deciding their prices in time period t. Profit maximization problem for the price resetting firm is:

$$\max_{P^*_{j,t}} E_t \sum_{i=0}^{\infty} (\beta\theta)^i \left(P^*_{j,t} Y_{j,t+i} - TC_{j,t+i}\right) \tag{21}$$

where $P^*_{j,t}$ is the optimal price. Substituting the expression for $Y_{j,t}$ from Equation (13) and replacing the $TC_{j,t+i} = mc_{j,t+i} \times Y_{j,t+i}$:

$$\max_{P^*_{j,t}} E_t \sum_{i=0}^{\infty} (\beta\theta)^i \left[P^*_{j,t} Y_{t+i} \left(\frac{P_{t+i}}{P^*_{j,t}}\right)^{\varphi} - Y_{t+i} \left(\frac{P_{t+i}}{P^*_{j,t}}\right)^{\varphi} mc_{j,t+i}\right] \tag{22}$$

subject to Equation (12). Solving for first order conditions leads to the expression for optimal price level:

$$P^*_{j,t} = \left(\frac{\varphi}{\varphi - 1}\right) E_t \sum_{i=0}^{\infty} (\beta\theta)^i mc_{j,t+i} \tag{23}$$

Since all the firms which reset the prices face the same marginal cost. Therefore, $P^*_{j,t}$ is same price for all $(1-\theta)$ price resetting firms. From Equation (14), $P_t^{1-\varphi} = \left[\int_0^1 P_{j,t}^{1-\varphi} dj\right]$, so equation for the price level can be written as:

$$P_t^{1-\varphi} = \int_0^{\theta} P_{t-1}^{1-\varphi} dj + \int_{\theta}^{1} P_t^{*1-\varphi} dj \tag{24}$$

solving the equation further gives the general price level :

$$P_t = \left[\theta P_{t-1}^{1-\varphi} + (1-\theta) P_t^{*1-\varphi}\right]^{\frac{1}{1-\varphi}} \tag{25}$$

2.2.3 Capital goods producing firm

We also introduce capital goods producing firms to the model. These firms transform investment goods into capital goods and provide capital goods to the intermediate producing firms. Their profit maximization is constrained by investment adjustment costs and under-utilization of the installed capacity. These firm choose the level of investment, installed capacity and capital goods and maximizes the following problem:

$$\max_{U_t, K_{t+1}, I_t} E_t \sum_{t=0}^{\infty} \Xi_{0,t} \left\{ R_t U_t K_t - P_t K_t \left[\Psi_1 (U_t - 1) + \frac{\Psi_2}{2} (U_t - 1)^2 \right] - P_t I_t \right\} \tag{26}$$

subject to

$$K_{t+1} = (1 - \delta) K_t + I_t \left[1 - \frac{\chi}{2} \left(\frac{I_t}{S_t^I I_{t-1}} - 1 \right)^2 \right] \tag{27}$$

where U is the installed capacity and Ψ_1, Ψ_2 are sensitivity parameters to installed capacity. The second part in the R.H.S. of capital accumulation equation (27) is investment adjustment cost. χ is the investment sensitivity parameter. S_t^I is the investment productivity shock:

$$log S_t^I = \rho_1 log S_{t-1}^I + \epsilon_{(I,t)} \tag{28}$$

where $\epsilon_{(I,t)}$ is an i.i.d. shock with $\epsilon_{(I,t)} \sim N(0, \sigma^I)$. Solving for the first order conditions for this problem, we get:

$$\frac{R_t}{P_t} = \Psi_1 + \Psi_2 (U_t - 1) \tag{29}$$

$$Q_t = E_t \Xi_{t,t+1} \left\{ Q_{t+1}(1-\delta) + R_{t+1}U_{t+1} - P_{t+1}\left[\Psi_1(U_{t+1}-1)\frac{\Psi}{2}(U_{t+1}-1)^2 \right] \right\} \tag{30}$$

$$\begin{aligned} P_t - Q_t \left[1 - \frac{\chi}{2}\left(\frac{I_t}{S_t^I I_{t-1}} - 1 \right)^2 - \chi \left(\frac{I_t}{S_t^I I_{t-1}} \right) \left(\frac{I_t}{S_t^I I_{t-1}} - 1 \right) \right] \\ = \chi E_t \left[\left(\frac{\Xi_{t,t+1} Q_{t+1}}{S_{t+1}^I} \right) \left(\frac{I_{t+1}}{I_t} \right)^2 \left(\frac{I_t}{S_t^I I_{t-1}} - 1 \right) \right] \end{aligned} \tag{31}$$

Here Q is the Tobin's Q. It is the Lagrange multiplier for the capital stock accumulation and represents the shadow price for capital.

2.3 Government

In the model, we assume that government does not issue currency and has two sources to obtain funds: one, it imposes lump-sum taxes on households and second, it issues bonds of short and long-term maturity to finance its expenditure. Therefore, government faces the following budget constraint:

$$\frac{B_{S,t+1}}{R_{S,t}^B} - B_{S,t} + \frac{B_{L,t+1}}{R_{L,t}^B} - \frac{B_{L,t}}{\prod_{i=2}^{N_L} R_{S,t+i-1}^B} = G_t P_t - T_t \tag{32}$$

Government alters fiscal policy using two tools - by changing the government expenditure G_t and by changing the lump-sum tax T_t. We further assume that government follows the following fiscal rule to maintain the debt-stability:

$$\frac{Z_t}{\bar{Z}} = \left(\frac{Z_{t-1}}{\bar{Z}}\right)^{\gamma_z} \left[\left(\frac{B_{S,t}/Y_{t-1}P_{t-1}}{\bar{B}_S/\bar{Y}\bar{P}}\right)\left(\frac{B_{L,t}/Y_{t-1}P_{t-1}}{\bar{B}_L/\bar{Y}\bar{P}}\right)\right]^{(1-\gamma_z)\phi_z} S_t^Z \tag{33}$$

where γ_z is the smoothing parameter. Z_t a vector of fiscal policy instruments, $Z_t = [G_t, T_t]$. S_t^Z is a fiscal policy shock:

$$logS_t^Z = \rho_Z logS_{t-1}^Z + \epsilon_{Z,t} \tag{34}$$

where $\epsilon_{Z,t}$ is an i.i.d. shock with $\epsilon_{Z,t} \sim N(0, \sigma^Z)$.

2.4 Central Bank

Central bank or the monetary authority sets the interest rate keeping in mind two broad objectives - price stability and economic growth. We assume that central bank follows a simple Taylor rule (Taylor, 1993):

$$\frac{R_{S,t}^B}{\bar{R}_S^B} = \left(\frac{R_{S,t-1}^B}{\bar{R}_S^B}\right)^{\gamma_R} \left[\left(\frac{Y_t}{\bar{Y}}\right)^{\gamma_Y}\left(\frac{\Pi_t}{\bar{\Pi}}\right)^{\gamma_\pi}\right]^{1-\gamma_R} S_t^m \tag{35}$$

where γ_R is the smoothing parameter and γ_Y , γ_π are interest rate sensitivity parameters of output and inflation and Π_t is the inflation rate

S_t^m is the monetary policy shock and follows the AR(1) process:

$$logS_t^m = \rho_m logS_{t-1}^m + \epsilon_{m,t} \tag{36}$$

where $\epsilon_{m,t}$ is an i.i.d. shock with $\epsilon_{m,t} \sim N(0, \sigma^m)$.

2.5 Equilibrium

We close the model with the equilibrium condition:

$$Y_t = C_t + I_t + G_t \tag{37}$$

3 Estimation

In this section we take the model to real data and discuss the estimation procedure of the structural model laid down in previous section. The model is estimated using the quarterly data for the Indian economy between the period April 2000-March 2020. Six observable variables - government final expenditure, private final consumption, gross fixed capital formation (GFCF), WPI, yields on 3-months maturity and 10-year maturity bonds. GFCF is taken as the proxy for investment and WPI is taken as proxy for inflation. We choose WPI as the measure of inflation because WPI was targeted by RBI until 2014. Afterwards, RBI started targeting CPI. Three variables - government final cosumption expenditure, private final consumption and GFCF are taken with seasonal adjustment and at their first difference. Data is collected from *Handbook of Statistics*, RBI and Fedrel Reserve Economic Data (FRED).

First, we calibrate some of the parameters which determine the steady-state. For this purpose, we fall back on the prior DSGE literature. Details of calibration are given in Table 1.

Table 1: Calibration of Parameters

Parameter	Description	Value	Source
δ	Depreciation rate	0.025	Banerjee & Basu (2019)
θ	Price stickiness parameter	0.75	Goyal (2011)
φ	Elasticity of substitution between intermediate goods	7.02	Levine et al. (2012)
ϕ_c	Habit persistence parameter	0.67	Goyal & Kumar (2018)
α	Share of capital	0.30	Banerjee & Basu (2019)
η	Coefficient of Relative risk aversion	2.0	Levine et al. (2012)
ω	Marginal disutility of labour (Inverse of Frisch elasticity of labor)	3.00	Anand & Prasad (2010); Ghate et al. (2018)
γ_R	Interest rate smoothing parameter	0.8	Banerjee et al. (2020)
γ_Y	Interest rate sensitivity of output	0.5	Taylor (1993)
γ_π	Interest rate sensitivity of inflation	1.5	Taylor (1993)
N_L	Maturity of long term bond	40	Author's determination

In second approach, we estimate the remaining parameters which are important for shock propagations. For estimation purpose, we apply Bayesian methodology. It is state of the art technique for the estimation of modern dynamic structural macroeconomic models. One advantage of Bayesian estimation is that it uses prior information about parameters into the estimation process. This prior information is expressed in the form of distribution i.e. priori. Therefore, it allows for a more informed and robust estimation of the parameters. In a way, it involves deriving posterior distribution of a parameter i.e. posteriori conditional upon already available information. According to Bayes theorem, the posterior distribution of parameters is given by:

$$p(\theta|Y^T) = \frac{L(Y^T|\theta)p(\theta)}{\int L(Y^T|\theta)p(\theta)d\theta} \tag{38}$$

where $p(\theta)$ is the prior associated with the parameter, $L(Y^T|\theta)$ is the likelihood of data with T observations. $\int L(Y^T|\theta)p(\theta)d\theta$ is the marginal of likelihood. $p(\theta|Y^T)$ is the posterior. So, posterior is proportional to likelihood multiplied by the prior. A closed form analytical solution is not possible, so, Markov Chain Monte-Carlo Metropolis-Hastings(MCMC-MH) algorithm[3] is used to obtain the posterior distribution.

Priors and Posteriors

Defining the prior distributions for parameters is the first step in Bayesian estimation. We define priors except for the parameters whose values are fixed in calibration. Our choice for priors is guided by both theoretical implications of model and empirical evidence. In literature, some general rules are followed in assigning priors, like *normal* distribution is used when more information about priors is required, *inverse gamma* distribution is used for non-negative constraints, *beta* distribution is used for fractions. Since there is a lack of existing empirical DSGE literature in Indian context, so we follow prior distributions for some parameters from empirical studies on developed countries. We choose *beta* distribution for autoregressive parameters because of the restriction to lie between zero and one, *inverse gamma* is used for standard errors of shock processes because it supports all positive values of parameters and eases the computational burden in estimation (following Banerjee et al. (2018); Peiris et al. (2010)). In India, there is little evidence on policy reaction function, so following (Saxegaard et al., 2010), we choose *uniform* distribution for monetary policy parameters. Details of priors is given in second and third columns of Table 2.

[3]The Metropolis-Hastings algorithm is a simple algorithm for producing samples from distributions which are otherwise difficult to sample. It works by simulating a Markov Chain. Detailed explanations in Chib & Greenberg (1995); An & Schorfheide (2007)

Table 2: Priors and Posteriors

Parameter	Density	Priori		Posteriori		
		Mean	Standard deviation	Mean	90 % confidence interval	
γ_G	Uniform	0.5	0.2829	0.6149	0.5073	0.757
γ_T	Uniform	0.5	0.2829	0.3908	0.3116	0.4572
ϕ_G	Uniform	-0.25	0.1443	0.1798	0.2361	0.0978
ϕ_T	Uniform	0.5	0.2887	0.9034	0.7765	0.9948
ρ_P	Beta	0.5	0.25	0.7078	0.5046	0.9266
ρ_L	Beta	0.5	0.25	0.8354	0.7701	0.8905
ρ_I	Beta	0.5	0.25	0.7429	0.6249	0.9172
ρ_A	Beta	0.5	0.25	0.2939	0.1873	0.3975
ρ_G	Beta	0.5	0.25	0.5325	0.4718	0.5712
ρ_T	Beta	0.5	0.25	0.5575	0.4052	0.761
ρ_m	Beta	0.5	0.25	0.6775	0.6144	0.7239
ρ_{BL}	Beta	0.5	0.25	0.8935	0.812	0.9931
Exogenous shocks						
ϵ_P	inverse gamma	1	Inf	0.6732	0.3423	0.9941
ϵ_L	inverse gamma	1	Inf	0.5635	0.3082	0.8906
ϵ_I	inverse gamma	1	Inf	0.4044	0.3414	0.4656
ϵ_A	inverse gamma	1	Inf	0.2626	0.1833	0.3599
ϵ_G	inverse gamma	1	Inf	0.3019	0.1996	0.3961
ϵ_T	inverse gamma	1	Inf	0.6284	0.2936	0.916
ϵ_m	inverse gamma	1	Inf	0.2349	0.2091	0.2593
ϵ_{BL}	inverse gamma	1	Inf	0.1188	0.1176	0.1205
ϵ_{DU}	inverse gamma	1	Inf	0.4124	0.2622	0.592
ϵ_{markup}	inverse gamma	1	Inf	0.4869	0.4183	0.5737

4 Estimation Results

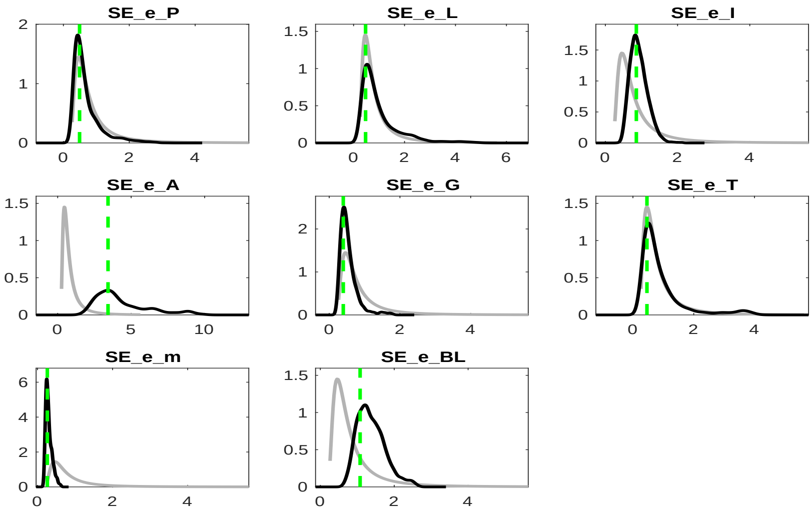
After Bayesian estimation[4], posteriors of estimated parameters are given in the fourth and fifth columns of Table 2. The posterior means are reported subject to posterior standard deviations with 90% high powered density (HPD)[5] confidence interval. As we see, posterior means for almost all estimated parameters are very similar to their prior means and fall in 90% HPD interval.

Figures 1 & 2 give a visual representation of prior and posterior distribution for estimated parameters. The grey line shows the prior density and black thick line shows the posterior density. The green dotted line is the posterior mode. We see from the figures that posterior modes are different from prior modes which suggests that posteriors are generated based on the information from observables. We also observe that posteriors distributions are different from their priors, which suggests that there is no identification issue and parameters are well identified.

Figure 3 represents the diagnostics statistics for multivariate convergence following Brooks & Gelman (1998). Here 'interval' refers to 80% quantile range, 'm2' and 'm3' refer to second and third moments. These three multivariate figures represent convergence indicators for all parameters together. Convergence is indicated by the two lines, red and blue, stabilizing and being close to each other.

[4]Estimation is done using Dynare 5.1.

[5]It expresses concentration of maximum values within 90% confidence interval.



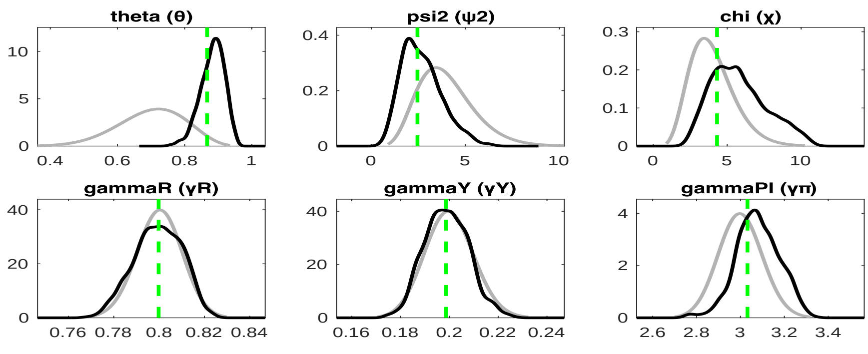


Figure 1: Priors and Posteriors 1

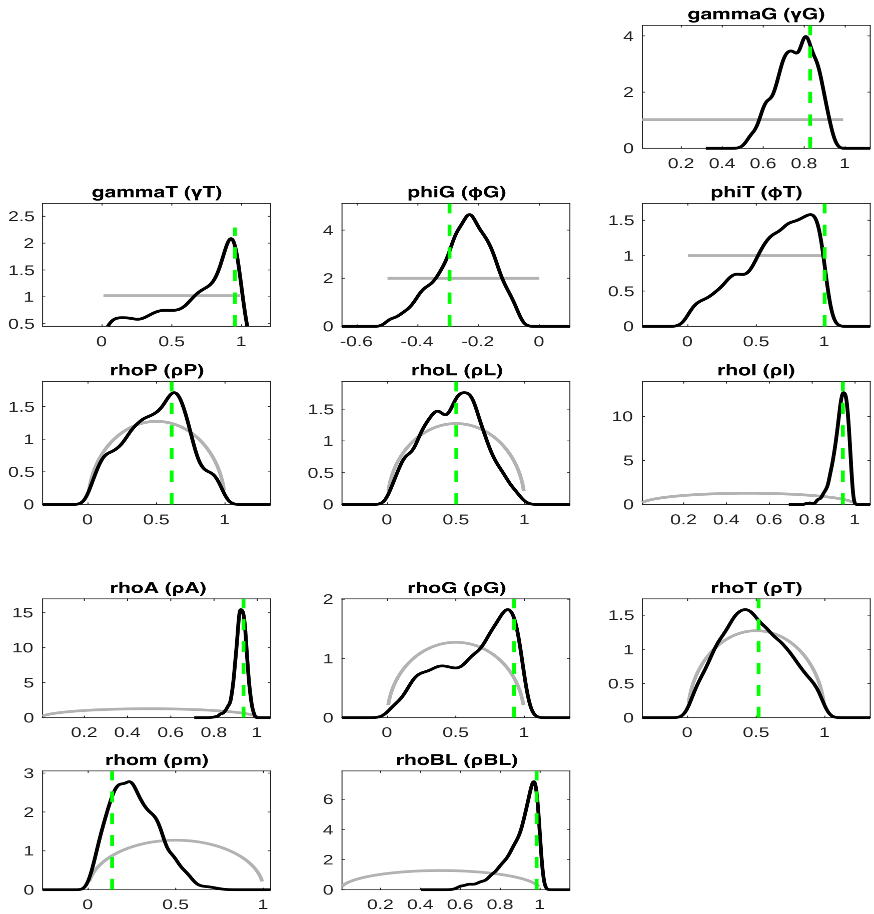


Figure 2: Priors and Posteriors 2

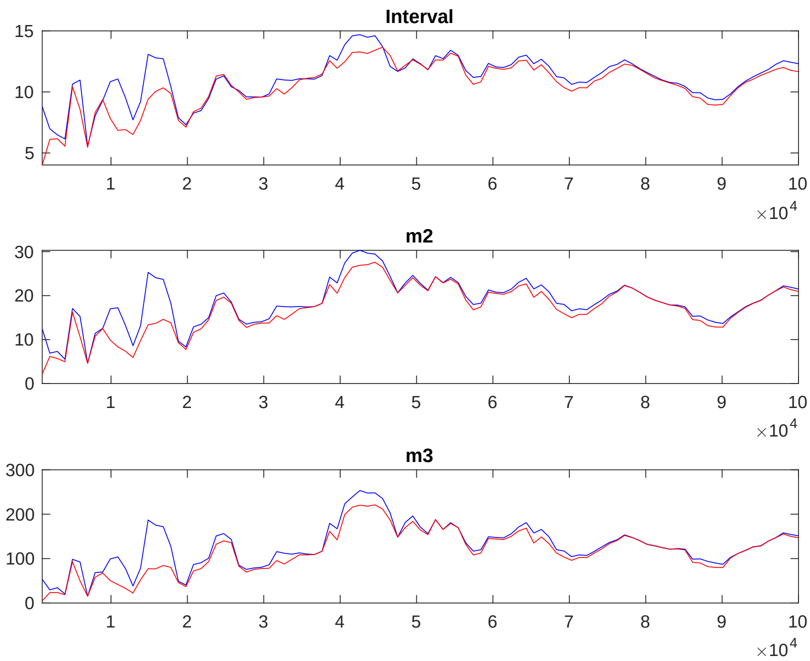


Figure 3: Multivariate Convergence Plots

Empirical Fit

To evaluate the model's empirical performance, we compare the second moments implied by the estimation with the moments from actual data. Table 3 compares the standard deviation of observed variables obtained after estimation with the real data. Model somewhat over predicts volatilities of key macro models but it is able to generate volatile term-premium which is comparable to the real data.

Table 3: Moments Comparison

Standard Deviation		
Variable	Data	Model
Consumption	2.03	2.71
Investment	2.79	3.80
Inflation	0.23	0.73
Term-Premium	1.37	1.23

Variance Decomposition

In this section, we discuss the contribution of key structural shocks in explaining the variance of endogenous macroeconomic variables.

Table 4: Variance Decomposition of key variables

Variables / Shocks	ϵ_P	ϵ_A	ϵ_G	ϵ_m	ϵ_{BL}	ϵ_{markup}
Y	91.20	2.45	0.14	1.35	0.14	4.33
C	98.60	0.27	0.04	0.09	0.01	0.47
I	58.11	11.30	1.29	4.46	1.38	17.73
G	50.86	4.38	9.50	5.04	8.43	7.17
π	29.42	16.06	0.10	29.64	0.17	28.82
R_BS	34.75	18.35	0.37	13.75	0.39	31.79
R_BL	66.34	9.21	0.88	2.31	0.61	13.54

Table 4 gives the results of variance decomposition. From the table, we find that most of the fluctuation in output and consumption is explained by preference shocks. Monetary policy shock has little impact on output fluctuations which is in line with the empirical literature on monetary transmission in India. Monetary policy shock is more prevalent in explaining inflation and short-term interest rate. Our inclusion of shock to long-term government bonds has negligible effects on variables except for government spending. As a whole, preference shock explains the major part of fluctuations. Policy shocks remain weak. Monetary and markup shocks are somewhat responsible for nominal variables like inflation and interest rates on short-term bonds.

Impulse Response Analysis

One important way to test the model is how it responds with various economic shocks. We introduce four basic shocks along with long-term bonds shock to different variables included in the model. These shocks enter the model through exogenous shocks (ϵ). Productivity shock enters through ϵ_A, preference shock through ϵ_P, monetary shock through ϵ_m and government expenditure shock through ϵ_G. Performance of the model is illustrated by impulse response functions (IRF). IRFs shows the percentage deviations from steady-state of each variable over a period of time. Figures 4 - 8 report the Bayesian impulse responses for these five shocks. Bayesian IRFs are the mean impulse responses. The gray shaded areas are the highest posterior density intervals (Highest Posterior Density Interval (HPDI)).

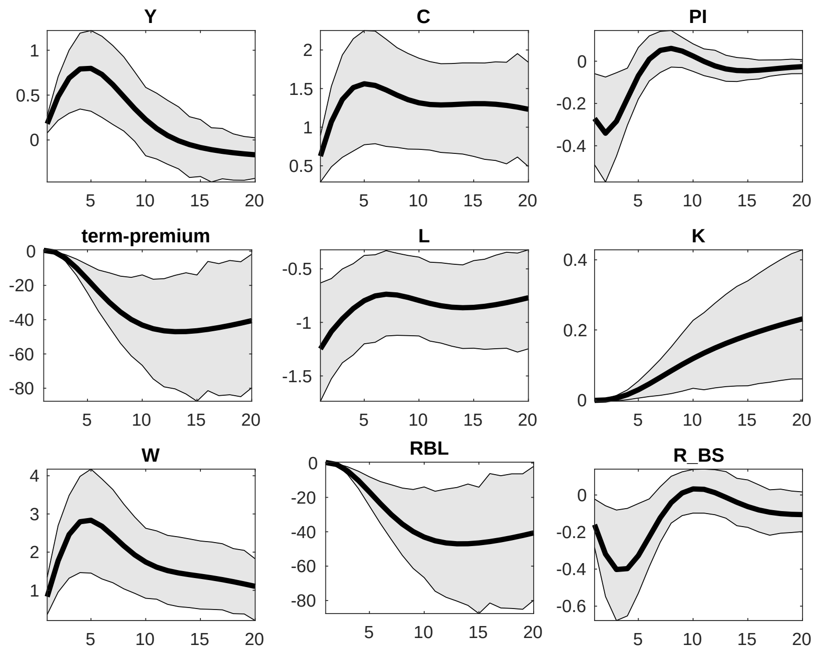


Figure 4: Productivity Shock

Figure 4 shows the impulse responses to a positive one standard deviation shock to technology. An increase in technology increases consumption because households feel wealthy due to increased output and economic activity. Since marginal cost decreases with an improvement of technology, inflation declines, which, in turn, reduces the monetary policy rate (short-term bond rate in our case). Term-premium shape is in line with the view that term-premium should be contractionary, i.e. lower in times of economic growth (Campbell & Cochrane, 1999)

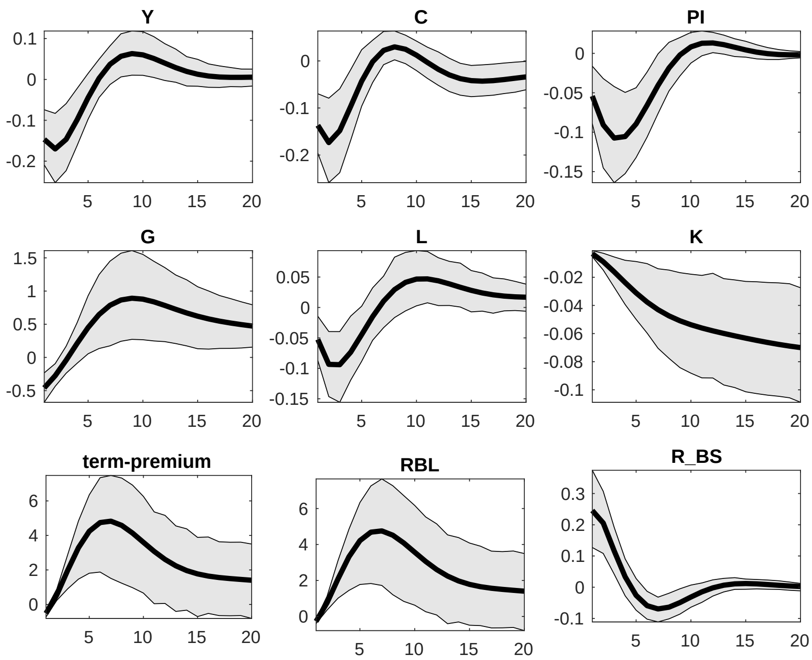


Figure 5: Monetary Policy Shock

Figure 5 plots the impulse responses to a contractionary monetary policy shock which is defined as a positive shock to the interest rate on short-term bond. Unlike technology shock, monetary policy shock implies a correlation between consumption and inflation. A shock to the short-term rate works as a signal for consumers to spend less in the current period. Decreased consumption and lower output slow down inflation. The monetary shock causes bond prices to fall. The term-premium shows an increase after the shock. This behaviour of term premium is consistent with Rudebusch & Swanson (2012)

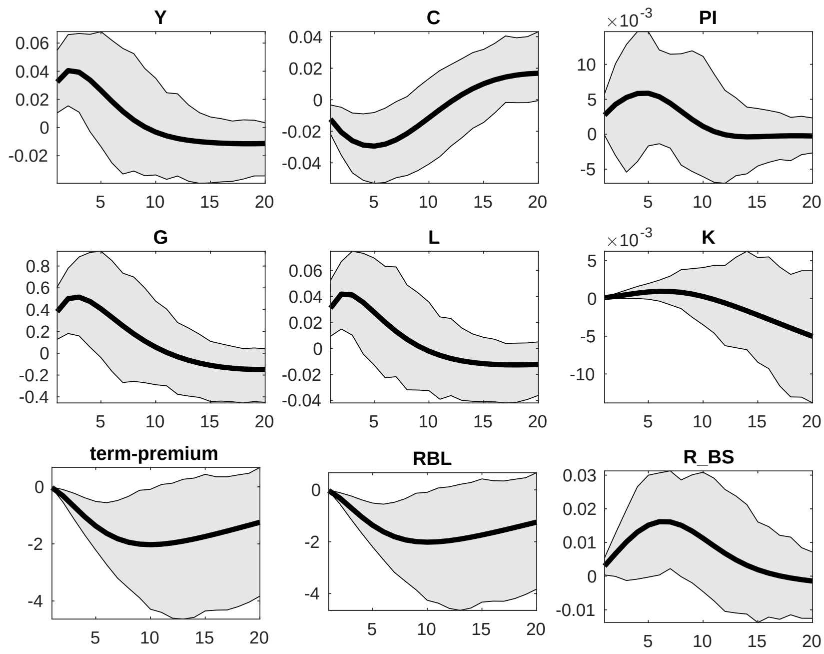


Figure 6: Government Expenditure Shock

We analyse the positive shock to government expenditure in Figure 6. Higher demand from the government's side put upward pressure on prices, followed by interest rate increase. Effect on private consumption is very small, which can be attributed to higher interest rate and higher prices also. Therefore, we can say that there is no direct crowding out effect due to government expenditure.

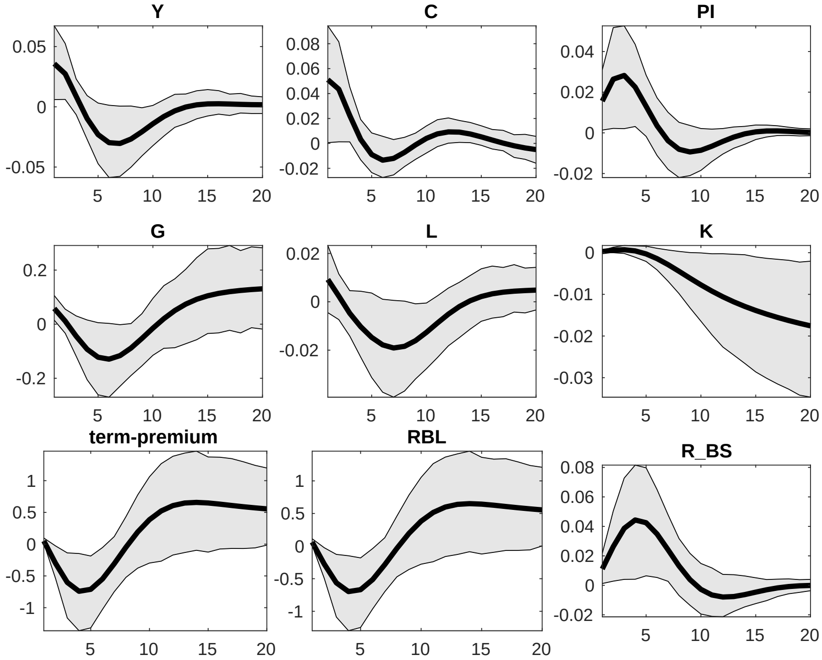


Figure 7: Preference Shock

Figure 7 shows the responses to consumption innovations, i.e., the preference shock. A positive preference shock increases consumption. Higher demand increases production and hence inflation rises. Higher production and inflation induce higher interest rates (from Taylor rule in Equation (35))

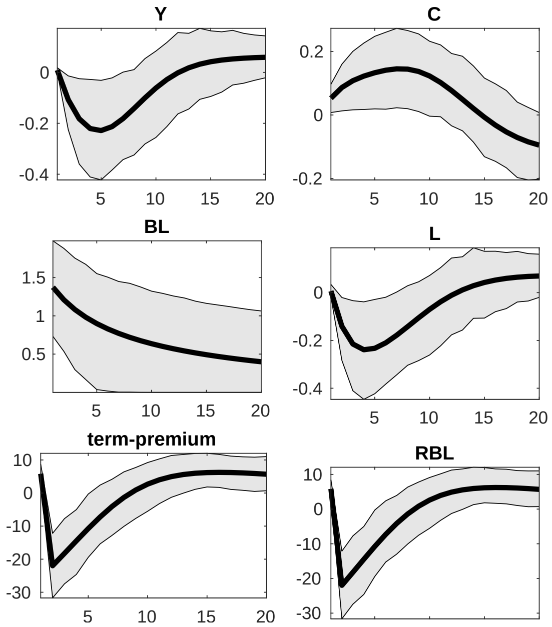


Figure 8: Shock to Long-Term Bonds

Figure 8 shows the impulse responses to a positive shock to the long term government bonds. Long term bond holdings by households is maximum at period zero and gradually returns to its steady-state level. The term premium first declines by around 20 basis points. Decline is maximum in the impact period; it reverts back to the steady-state subsequently. As evident from the figure, a supply shock to the long-term bonds lowers the long-term interest rate with relatively lower impact on short-term interest rate. Term premium movement is reflected in the long-term interest rate which is consistent with the preferred-habitat theory.

5 Conclusion

The study connects the term structure of interest rates with a New-Keynesian DSGE model in an alternative, less cumbersome approach. This kind of exercise is beneficial for both sides, macroeconomy and the yield curve dynamics, because DSGE models provide a robust framework to understand the dynamics of key macroeconomic variables and they should also incorporate long term bonds. We introduce portfolio adjustment cost, which makes different maturities bond imperfect substitutes. This is first such attempt for the Indian economy to integrate term-premium within a structural model. Results from the Bayesian estimation suggest that model is able to match the moments of term-premium and macro data reasonably well. It is able to generate sufficient volatile term premium. Results from impulse responses show that our variable of interest, term-premium behaves in line with the previous studies. Monetary policy influences the long term rate and term premium along with the short-term rates. Shocks to government expenditure are moderate and not long-lasting on term structure.

The proposed model can be improved further by including money demand, financial intermediaries to understand term structure dynamics more effectively.

Appendix

Households:

Lagrangian for Households

$$\begin{aligned}\mathcal{L} = E_t \sum_{t=0}^{\infty} \beta^t S_t^P \left[\frac{(C_{j,t} - \phi_c C_{j,t-1})^{1-\eta}}{1-\eta} - S_t^L \frac{L_{j,t}^{1+\omega}}{1+\omega} \right] \\ - \lambda_{j,t} \left[C_{j,t} P_t + \frac{B_{S,j,t+1}}{R_{S_t}^B} + \frac{B_{L,j,t+1}}{R_{L_t}^B} \left(1 + \left[\frac{\vartheta_L}{2} \left(\frac{B_{L,t+1}}{B_{L,t}} \right)^2 \right] Y_t \right) \right. \\ \left. - W_t L_{j,t} - B_{S,j,t} - \frac{B_{L,j,t}}{\prod_{i=2}^{N_L} R_{S,t+i-1}^B} + T_{j,t} \right]\end{aligned} \tag{39}$$

First order conditions:

$$\frac{\partial \mathcal{L}}{\partial C_{j,t}} = S_t^P (C_{j,t} - \phi_c C_{j,t-1})^{-\eta} - \phi_c \beta E_t [S_{t+1}^P (C_{j,t+1} - \phi_c C_{j,t})^{-\eta}] - \lambda_{j,t} P_t = 0 \tag{40}$$

$$\frac{\partial \mathcal{L}}{\partial L_{j,t}} = -S_t^P S_t^L L_{j,t}^{\omega} + \lambda_{j,t} W_t = 0 \tag{41}$$

$$\frac{\partial \mathcal{L}}{\partial B_{S,j,t+1}} = -\frac{\lambda_{j,t}}{R_{S,t}^B} + \beta E_t \lambda_{j,t+1} = 0 \tag{42}$$

$$\begin{aligned}\frac{\partial \mathcal{L}}{\partial B_{L,j,t+1}} = -\frac{\lambda_{j,t}}{R_{L,t}^B} \left[1 + \frac{3}{2} \vartheta_L \left(\frac{B_{L,t+1}}{B_{L,t}} \right)^2 Y_t \right] - \beta E_t \lambda_{j,t+1} \left[\left(\frac{1}{\prod_{i=2}^{N_L} R_{S,t+i-1}^B} \right) \right. \\ \left. + \left(\frac{1}{R_{L,t+1}^B} \right) \vartheta_L \left(\frac{B_{L,j,t+2}}{B_{L,j,t+1}} \right)^3 Y_{t+1} \right] \\ = 0\end{aligned} \tag{43}$$

Firms:

Maximization problem for final goods producing firm:

$$\max_{Y_{j,t}} P_t Y_t - \int_0^1 P_{j,t} Y_{j,t} dj \tag{44}$$

substituting the expression for Y from (11)

$$\max_{Y_{j,t}} P_t \left(\int_0^1 Y_{j,t}^{\frac{\varphi-1}{\varphi}} dj \right)^{\frac{\varphi}{\varphi-1}} - P_{j,t} \int_0^1 Y_{j,t} dj \tag{45}$$

First order conditions:

$$P_t \left(\int_0^1 Y_{j,t}^{\frac{\varphi-1}{\varphi}} dj \right)^{\frac{1}{\varphi-1}} Y_{j,t}^{\frac{-1}{\varphi}} - P_{j,t} = 0 \tag{46}$$

aggregator function may also be written as:

$$Y_t^{\frac{1}{\varphi}} = \left(\int_0^1 Y_{j,t}^{\frac{\varphi-1}{\varphi}} dj \right)^{\frac{1}{\varphi-1}} \tag{47}$$

putting this back in the first order condition:

$$P_t Y_t^{\frac{1}{\varphi}} Y_{j,t}^{\frac{-1}{\varphi}} - P_{j,t} = 0 \tag{48}$$

$$Y_{j,t} = Y_t \left(\frac{P_t}{P_{j,t}} \right)^{\varphi} \tag{49}$$

Lagrangian for Intermediate goods firm:

$$\mathcal{L} = W_t L_{j,t} + R_t U_t K_{j,t} + \nu_{j,t} \left(Y_{j,t} - A_t (U_t K_{j,t})^{\alpha} L_{j,t}^{1-\alpha} \right) \tag{50}$$

First order conditions:

$$\frac{\partial \mathcal{L}}{\partial L_{j,t}} = W_t - (1-\alpha)\nu_{j,t} A_t (U_t K_{j,t})^{\alpha} L_{j,t}^{\alpha} = 0 \tag{51}$$

$$\frac{\partial \mathcal{L}}{\partial K_{j,t}} = R_t U_t - \alpha \nu_{j,t} A_t (U_t K_{j,t})^{\alpha-1} L_{j,t}^{1-\alpha} = 0 \tag{52}$$

Since total cost

$$TC_{j,t} = W_t L_{j,t} + R_t K_{j,t} \tag{53}$$

substituting the expressions for labour and capital from first order conditions:

Lagrangian for Capital Producing Firm:

$$\begin{aligned} \mathcal{L} = E_t \sum_{t=0}^{\infty} \Xi_{0,t} \left\{ R_t U_t K_t - P_t K_t \left[\Psi_1 (U_t - 1) + \frac{\Psi_2}{2} (U_t - 1)^2 \right] - P_t I_t \right\} \\ - Q_t \left[K_{t+1} - (1-\delta) K_t - I_t \left[1 - \frac{\chi}{2} \left(\frac{I_t}{S_t^I I_{t-1}} - 1 \right)^2 \right] \right] \end{aligned} \tag{54}$$

First order conditions:

$$\frac{\partial \mathcal{L}}{\partial U_t} = \Xi_{0,t} R_t K_t - \Xi_{0,t} P_t K_t \Psi_1 - \Xi_{0,t} P_t K_t \Psi_2 (U_t - 1) = 0 \tag{55}$$

$$\frac{\partial \mathcal{L}}{\partial K_{t+1}} = E_t \Xi_{t,t+1} R_{t+1} U_{t+1} - E_t \Xi_{t,t+1} P_{t+1} \left[\Psi_1 (U_{t+1} - 1) + \frac{\Psi_2}{2} (U_{t+1} - 1)^2 \right] - Q_t + E_t \Xi_{t,t+1} Q_{t+1} (1$$

$$\frac{\partial \mathcal{L}}{\partial I_t} = -P_t + \frac{\partial E_t \sum_{t=0}^{\infty} \Xi_{0,t} \left\{ Q_t I_t \left[1 - \frac{\chi}{2} \left(\frac{I_t}{S_t^I I_{t-1}} - 1 \right)^2 \right] \right\}}{\partial I_t} = 0 \quad (57)$$

further,

$$\begin{aligned} &\frac{\partial E_t \sum_{t=0}^{\infty} \Xi_{0,t} \left\{ Q_t I_t \left[1 - \frac{\chi}{2} \left(\frac{I_t}{S_t^I I_{t-1}} - 1 \right)^2 \right] \right\}}{\partial I_t} \\ &\quad = Q_t - \frac{\chi}{2} \left\{ Q_t \left(\frac{I_t}{S_t^I I_{t-1}} - 1 \right)^2 + Q_t I_t 2 \left(\frac{I_t}{S_t I_{t-1}} - 1 \right) \left(\frac{1}{S_t^I I_{t-1}} \right) \right. \\ &\qquad \left. - \Xi_{t,t+1} E_t \left[Q_{t+1} I_{t+1} 2 \left(\frac{I_{t+1}}{S_{t+1}^I I_t} - 1 \right) \frac{I_{t+1}}{I_t^2} \right] \right. \end{aligned} \quad (58)$$

Then,

$$\begin{aligned} &- P_t + Q_t \left[1 - \frac{\chi}{2} \left(\frac{I_t}{S_t I_{t-1}} - 1 \right)^2 - \chi \frac{I_t}{S_t I_{t-1}} \left(\frac{I_t}{S_t^I I_{t-1}} - 1 \right) \right] \\ &\qquad + \chi E_t \left[\left(\frac{\Xi_{t,t+1} Q_{t+1}}{S_{t+1}^I} \right) \left(\frac{I_{t+1}}{I_t} \right)^2 \left(\frac{I_{t+1}}{S_{t+1}^I I_t} - 1 \right) \right] = 0 \end{aligned} \quad (59)$$

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