Information in the Yield Curve: an Extended Macro-Finance Approach

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Overview

- Introduction
- Macro-Finance framework
- Econometric issues
- Empirical findings
- Conclusions

The goal of the paper is to (re-) assess the (macroeconomic) information content of yield curve using a medium-scale macro-finance model:

- Motivation: the growing empirical evidence showing that financial shocks (next to macroeconomic shocks) are important drivers of the yield curve (liquidity shocks, CP factors,...)
- Premise: financial and macroeconomic shocks have different information content and need to be differentiated.
- Differentiating shocks: decomposition of the term spread shows that the expectations and term premium components reflect different types of shocks (and information)
- Does differentiation between shocks (decomposition of the term spread) improve predictive performance of yield curve?

Contribution of this paper:

- Extend the benchmark macro-finance framework by integrating a set of (additional) factors:
  - Return-forecasting factor: shifts in risk appetite idisrupting traditional links between short and long rates, e.g. Cochrane and Piazzesi (2005, 2008), ...
  - Money market factors (flight to quality and counterparty risk), e.g. Feldhütter and Lando (2008).....
  - Stochastic endpoints (unit roots) for macroeconomic state, e.g. Joslin et al (2010), Dewachter and Lyrio (2006)...
- Use the extended model to assess the information content of term spread decompositions:
  - Business cycle conditions and predictions: e.g. Estrella and Mishkin (1996), Ang et al (2005)), Rudebusch and Williams (2009)....
  - Inflation expectations "scares": e.g. Mishkin (1990), Estrella and Mishkin (1997), Kozicki and Tinsley (2001),.Faust and Wright (2011)...

Macro-Finance models (and decompositions) are used as a theoretical framework to study macro-financial linkages (e.g. Ang and Piazzesi (2003),...):

- No-arbitrage condition linking short to long maturities interest rate:

$$y_t(m) = \frac{1}{m} \sum_{j=0}^{m-1} E_t(i_{t+j}) + \chi_t(m)$$

- Macro model linking (expected) interest rates and risk premium to the macroeconomic state:

$$E_t i_{t+j} = F(j, q_t, \pi_t, i_t, l_t), \quad \chi_t(m) = G(m, q_t, \pi_t, i_t, l_t)$$

- Resulting in a standard macro-finance model:

$$y_t(m) = \underbrace{\frac{1}{m} \sum_{j=0}^{m-1} F(j, q_t, \pi_t, i_t, l_t)}_{\text{Expectations component}} + \underbrace{G(m, q_t, \pi_t, i_t, l_t)}_{\text{Term premium}}$$

The extended macro-finance model incorporates trends, money market (liquidity) and risk premium factors.

- No-arbitrage condition relates short to long maturities interest rate:

$$y_t(m) = \frac{1}{m} \sum_{j=0}^{m-1} E_t(i_{t+j}) + \chi_t(m)$$

- Macro model linking (expected) interest rates and risk premium to the macroeconomic and financial state variables:

$$E_t i_{t+j} = F(j, \underbrace{q_t, \pi_t, i_t, \pi_t^*}_{\text{macro}}, \underbrace{l_{1,t}, l_{2,t}}_{\text{liquidity}}), \quad \chi_t = G(m, \underbrace{q_t, \pi_t, i_t, \pi_t^*}_{\text{macro}}, \underbrace{l_{1,t}, l_{2,t}}_{\text{liquidity}}, \underbrace{l_{3,t}}_{\text{risk}}).$$

- Resulting in the extended macro-finance model:

$$y_t(m) = \underbrace{\frac{1}{m} \sum_{j=0}^{m-1} F(j, q_t, \pi_t, i_t, l_{1,t}, l_{2,t})}_{\text{Expectations component}} + \underbrace{G(m, q_t, \pi_t, i_t, l_{1,t}, l_{2,t}, l_{3,t})}_{\text{Term premium}}$$

Macro-Finance Framework

The Macro-Finance framework

Linear, exponentially-affine pricing framework

State space dynamics:

- The dynamics for the state vector, X_t, is assumed to follow a VAR(I) dynamics:

$$X_t = C + \Phi X_{t-1} + D\varepsilon_t, \ \varepsilon_t \sim N(0, I)$$

- The state vector consists of eight (observed and latent) variables and shocks:

$$X_t' = [\underbrace{\pi_t, \quad q_t, \quad i_t^{cb},}_{\text{Obs. macro factors}} \quad \underbrace{l_{1,t}, \quad l_{2,t}, \quad l_{3,t},}_{\text{Unobs. finance factors}} \quad \underbrace{\pi_t^*, \quad \rho_t}_{\text{Unobs.stoch. trnds.}}]$$

$$\varepsilon_t' = [\underbrace{\varepsilon_{\pi,t}, \quad \varepsilon_{q,t}, \quad \varepsilon_{i^{cb},t},}_{\text{Obs. macro shocks}} \quad \underbrace{\varepsilon_{l_1,t}, \quad \varepsilon_{l_2,t}, \quad \varepsilon_{l_3,t},}_{\text{Unobs. liq. and risk shocks}} \quad \underbrace{\varepsilon_{\pi^*,t}, \quad \varepsilon_{\rho,t}}_{\text{Unobs. perm. shock.}}]$$

- An economic interpretation for each latent factor/ shock is imposed by means of identification restrictions.

The Macro-Finance framework

Linear, exponentially-affine pricing framework

Exponentially affine pricing models are obtained under the following assumptions (see Duffee (2002)):

- Gaussian state space dynamics (identifying the relevant market historical probability measure, E_t):

$$X_t = C + \Phi X_{t-1} + D\varepsilon_t, \ \varepsilon_t \sim N(0, I)$$

- Exponentially-affine stochastic discount factor with linear price of risk specification (Duffee (2002)):

$$M_{t,t+1} = \exp(-i_t^{rf} - \tfrac{1}{2}\Lambda_t' S S' \Lambda_t - \Lambda_t' S \varepsilon_{t+1})$$

$$\Lambda_t = \Lambda_0 + \Lambda_1 X_t, \quad i_t^{rf} = \delta_0 + \delta_1 X_t$$

- Imposing the no-arbitrage assumption on (zero) coupon prices, $p_t(m)$:

$$p_t(m) = E_t\left[M_{t,t+1} p_{t+1}(m-1)\right], \ p_t(0) = 1$$

The Macro-Finance framework

Linear, exponentially-affine pricing framework

The exponentially-affine pricing model implies an affine yield curve representation:

$$
\begin{aligned}
y_t(m) \quad = \quad & A_y(m) + \\
& B_{y,\pi}(m)\pi_t + B_{y,q}(m)q_t + B_{y,i}(m)i_t^{cb} && \longleftarrow \text{Observed macro factors} \\
& B_{y,l_1}(m)l_{1,t} + B_{y,l_2}(m)l_{2,t} + B_{y,l_3}(m)l_{3,t} && \longleftarrow \text{Unobs. financial factors} \\
& B_{y,\pi^*}(m)\pi_t^* + B_{y,\rho}(m)\rho_t && \longleftarrow \text{Unobs. stochastic trends}
\end{aligned}
$$

with:

$$A_y(m) = -a_p(m)/m, \;\; B_y(m) = -b_p(m)/m$$

$$a(m) = a(m-1) + b(m)(C - D\Lambda_0) + \tfrac{1}{2} b(m)DD'b(m)' - \delta_0$$

$$b(m) = b(m-1)(\Phi - D\Lambda_1) - \delta_1.$$

The Macro-Finance framework

Linear, exponentially-affine pricing framework

Additional over-identifying restrictions link the P and Q dynamics:

- Latent factors obtain an economic or financial interpretation.
- The no-arbitrage restrictions become 'relevant', (see Joslin et al (2011) and Duffee (2011)).

Restrictions imposed:

- Over-identifying (cointegration) restrictions on the Φ matrix under the P-measure, allowing an interpretation of stochastic trends as long-run expectations for inflation and the real rate.
- Over-identiftying restrictions on the prices of risk Λ_1 to allow for a return-forecasting factor (l_3).
- Identification restrictions on δ_1 for the risk-free rate and the relation to the money market factors (l_1 and l_2).

Restrictions on the dynamics under the historical probability measure :

- π_t^* and ρ_t, are the long-run expectations for inflation and the real rate:

$$\lim_{s\to\infty} E_t \begin{bmatrix} \pi_{t+s} \\ y_{t+s} \\ i_{t+s}^{cb} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 0 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} \pi_t^* \\ \rho_t \end{bmatrix} = \begin{bmatrix} \pi_t^* \\ 0 \\ \rho_t + \pi_t^* \end{bmatrix}.$$

- Identification restrictions on Φ and D impose this interpretation on the state space:

$$\Phi = \begin{bmatrix} \Phi^{MM} & \Phi^{MI} & (\mathbf{I}-\Phi^{MM})\mathbf{T}^D \\ \Phi^{IM} & \Phi^{II} & -\Phi^{IM}\mathbf{T}^D \\ \mathbf{0} & \mathbf{0} & \mathbf{I} \end{bmatrix}, \; T^D = \begin{bmatrix} 1 & 0 \\ 0 & 0 \\ 1 & 1 \end{bmatrix},$$

$$\mathrm{mod}(eig(\Phi^{MM})) < 1, \text{ and } \mathrm{mod}(eig(\Phi^{II})) < 1,$$

$$C^M = -\Phi^{IM}\bar{C}^I, \; D^{M\xi} = (I - \Phi^{MM})T^D S^{\xi\xi}, \; D^{I\xi} = -\Phi^{IM} T^D S^{\xi\xi}.$$

The Macro-Finance framework

Identification restrictions on unobservable factors

Identification of the money market factors occurs by decomposing the TED spread (relative to a secured money market rate):

- $l_{1,t}$ and $l_{2,t}$ decompose the TED spread into T-bill and LIBOR spread:

$$i_t^{LIBOR} - i_t^{\text{T-bill}} = l_{1,t} + l_{2,t} \quad \longleftarrow \quad \text{TED spread}$$

$$i_t^{repo} - i_t^{\text{T-bill}} = l_{1,t} \quad \longleftarrow \quad \text{T-bill spread factor}$$

$$i_t^{LIBOR} - i_t^{repo} = l_{2,t} \quad \longleftarrow \quad \text{LIBOR spread factor}$$

- Money market factors are linked to the central bank rate:

$$i_t^{\text{T-bill}} = c + i_t^{cb} - l_{1,t} + \varepsilon_{i,t}$$

Over-identifying restrictions are imposed on the prices of risk: one-period risk premium is linearly related to a single risk factor (Cochrane and Piazzesi (2008)):

- $l_{3,t}$ is the "return-forecasting" (CP) factor:

$$eh_t(m) = b(m)D\Lambda_0 - \frac{1}{2}b(m)\Gamma SS'\Gamma' b(m)' + \left[\sum_{i=1}^{\dim X}\sum_{j=1}^{\dim X} b_{1,i}(m)D_{i,j}\Lambda_{j,6}\right]\mathbf{l}_{3,t}.$$

- Sufficient conditions for a return forecasting factor are (Cochrane and Piazzesi (2008)):

$$\Lambda_t = \Lambda_0 + \Lambda_1 X_t, \quad \Lambda_1 = \begin{bmatrix} 0 & \cdots & 0 & \Lambda_{1,6} & 0 & 0 \\ 0 & \ddots & 0 & \Lambda_{2,6} & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & \cdots & 0 & \Lambda_{8,6} & 0 & 0 \end{bmatrix}$$

The Macro-Finance framework

Linear, exponentially-affine pricing framework

The exponentially-affine pricing model implies an affine yield curve representation. All factors have an economic interpretation:

$$y_t(m) = A_y(m) +$$

$$\underbrace{B_{y,\pi}(m)\pi_t + B_{y,q}(m)q_t + B_{y,i}(m)i_t^{\text{cb}}}_{\text{Observed macroeconomic factors}} \quad \longleftarrow \text{Observed macro factors}$$

$$\underbrace{B_{y,l_1}(m)l_{1,t} + B_{y,l_2}(m)l_{2,t}}_{\text{Spread (liquidity) factors}} + \underbrace{B_{y,l_3}(m)l_{3,t}}_{\text{Risk attitude.}} \quad \longleftarrow \text{Unobs. financial factors}$$

$$\underbrace{B_{y,\pi^*}(m)\pi_t^* + B_{y,\rho}(m)\rho_t}_{\text{Long-run exp: infl. and real rate}} \quad \longleftarrow \text{Unobs. stochastic trends}$$

Empirical analysis

Empirical analysis

Data

Rejecting the expectations hypothesis

- Bond premia
- Term premia

Decomposing term spread dynamics

- Term spreads
- Expectations components

Information content of (decomposed) spreads

- Predicting economic growth (Estrella and Hardouvelis (1991))
- Inflation-change prediction equations (Mishkin (1990))

Empirical analysis

Data

Model is estimated on US data: 1960Q1 till 2008Q4.

- Quarter-by-quarter inflation (GDP deflator) rate (p.a. terms) are used. Source: Federal Reserve Economic Data archive (FRED).
- CBO output gap measure is used (no- real time data). Source: Congressional Budget Office.
- Fed fund rate is used as policy rate. Source FRED.
- LIBOR (US dollar) over the period 1986-2008. Source: BBA, British Bankers Association.
- Yield curve: 1/4, 1, 2, 3, 5, 10 yr. maturities. Source: Gürkaynak et al. (2006), CRSP, FRED.
- Inflation expectations: Average inflation expectations over 1 and 10 year horizon. Source: Survey of Professional Forecasters, FED Philadelphia.

The extended macro-finance model rejects the expectations hypothesis.

Statistical evidence: posterior density points at the significance of time-varying prices of risk:

- Interest rate risk (mon. policy shocks) is priced ($\Lambda_1 \neq 0$)

The model implies substantial variation in the bond premia (across the maturity spectrum):

- Explained variation in excess returns similar to that obtained by Cochrane and Piazzesi (2005).
- Return-forecasting factor implied by the model displays significant correlation to the CP factor.

There is evidence of economically significant variation in the term premium components for long maturities:

- The term premium dynamics are similar to the Kim and Wright (2005) measure.

Table: EXPECTED AND REALIZED EXCESS RETURNS

In-sample statistics

	Adj. R^2: 4-qtr holding period (k)			
maturity (n)	8 qtr	12 qtr	16 qtr	20 qtr
CP	29.90%	31.21%	33.07%	30.50%
EMF	36.15%	31.78%	31.51%	31.53%

	Adj. R^2: 8-qtr holding period (k)			
maturity (n)	8 qtr	12 qtr	16 qtr	20 qtr
CP	-	20,29%	22,05%	20,53%
EMF	-	40,89%	38,87%	39,44%

	Adj. R^2: 16-qtr holding period (k)			
maturity (n)	8 qtr	12 qtr	16 qtr	20 qtr
EMF	-	-	-	47,30%

Empirical analysis

Rejecting the expectations hypothesis: bond premia

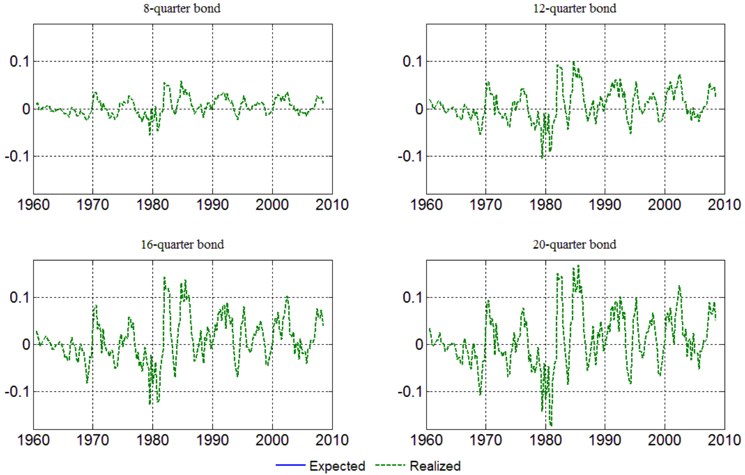
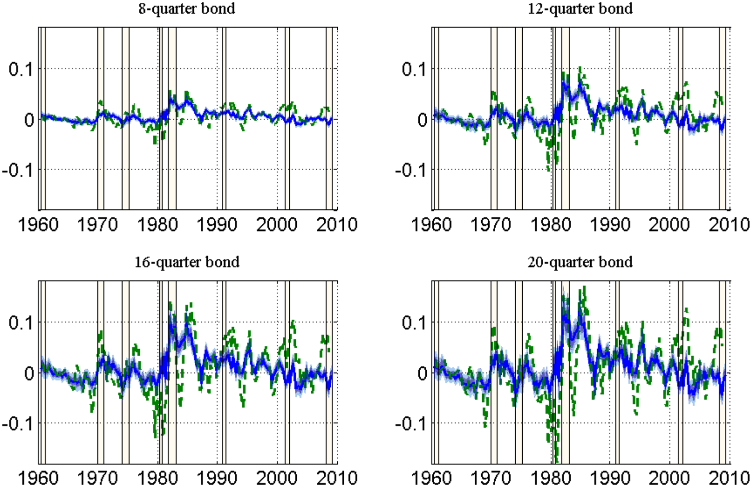


Figure: Realized excess returns (1-year holding period)

Figure: Excess return: (1-year holding period)



Empirical analysis

Rejecting the expectations hypothesis: CP factor

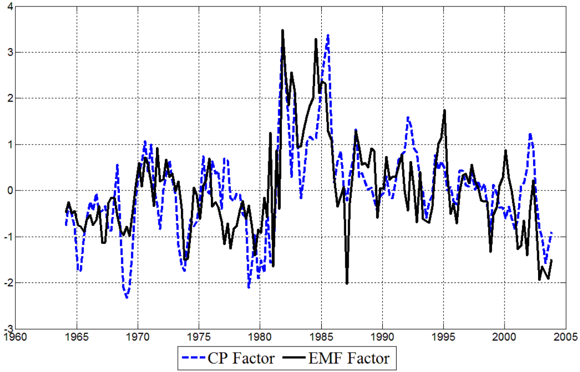


Figure: Return-forecasting factors: Cochrane and Piazzesi vs. EMF

Empirical analysis

Rejecting the expectations hypothesis: term premia

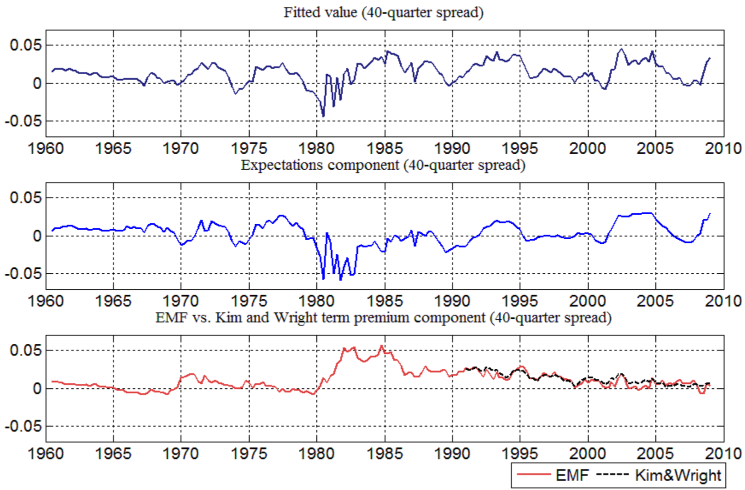
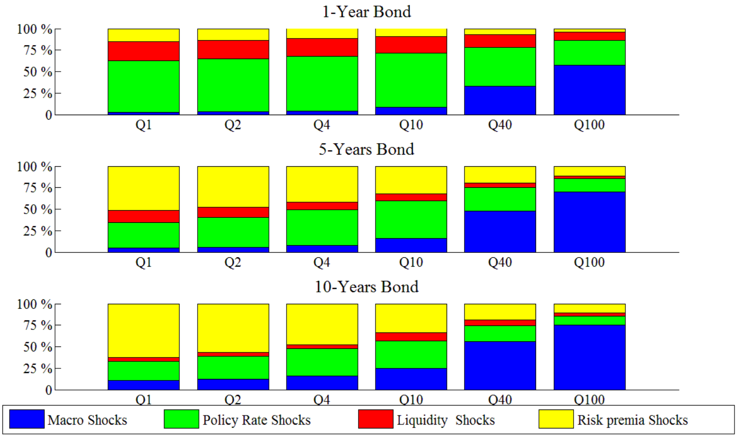


Figure: FIVE-YEAR SPREAD: EXPECTED AND TERM PREMIUM COMPONENTS

Empirical analysis

Decomposing yield dynamics:

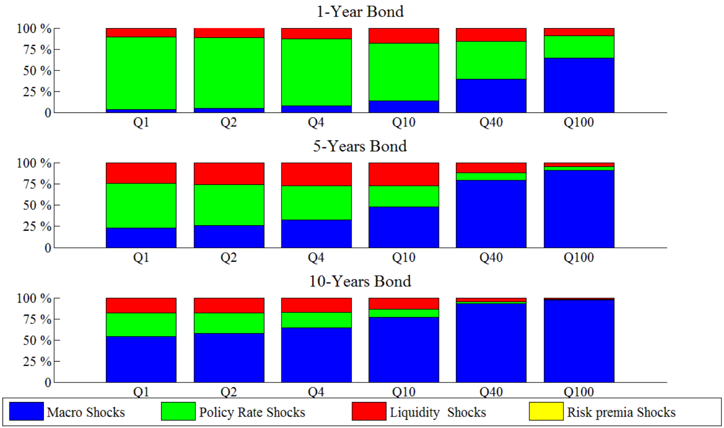
Figure: Variance decomposition yield



Empirical analysis

Decomposing yield dynamics: expectations component

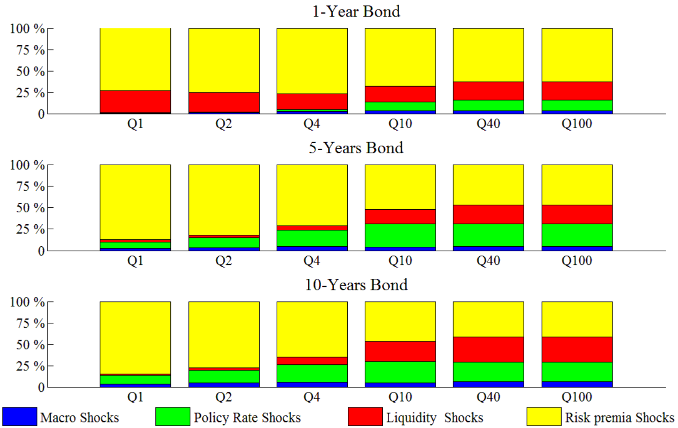
Figure: Variance decomposition yield: expectations comp.



Empirical analysis

Decomposing yield dynamics: term premium component

Figure: Variance decomposition yield: term premium comp.



Empirical analysis

Predicting economic growth

Base model. Prediction equation economic growth (e.g. Estrella Hardouvelis (1991), Estrella and Mishkin (1996)):

$$g_{t\to t+k} = \alpha_{k,m} + \beta_{k,m}(Spr_t^{(m)})) + \varepsilon_{k,m,t}$$

$$g_{t\to t+k} = \frac{4}{k}(\ln GDP_{t+k} - \ln GDP_t), \quad Spr_t^{(m)} = y_t(m) - y_t(1)$$

Alternative prediction regressions:

$$g_{t\to t+k} = \alpha_{k,m} + \beta_{k,m}^{EC}(Spr_t^{e,(k)} + \chi_t^{(k)})) + \beta_{k,m}^{TP}\chi_t^{(k)} + \varepsilon_{k,m,t}$$

$$g_{t\to t+k} = \alpha_{k,m} + \beta_{k,m}Spr_t^{(k)} + \gamma_k g_t + \delta_{k,m}y_t(1) + \varepsilon_{k,m,t}$$

$$g_{t\to t+k} = \alpha_{k,m} + \beta_{k,m}^{EC}(Spr_t^{e,(k)} + \chi_t^{(k)})) + \beta_{k,m}^{TP}\chi_t^{(k)} + \gamma_{k,m}g_t + \delta_{k,m}y_t(1) + \varepsilon_{k,m,t}$$

Table: FORECASTING ECONOMIC GROWTH (1 YEAR) USING 5 YR SPREAD

	Model 1	Model 2	Model 3	Model 4
α	0,023			
	(0,004)			
β	0,840			
	(0,214)			
β^{EC}	-			
	-			
β^{TP}	-			
	-			
γ	-			
	-			
δ	-			
	-			
Adj.-R^2	0,147			

$$g_{t\rightarrow t+k} = \alpha_{k,m} + \beta_{k,m} Spr_t^{(m)} + \varepsilon_{k,m,t}$$

Table: FORECASTING ECONOMIC GROWTH (1 YEAR) USING 5 YR SPREAD

	Model 1	Model 2	Model 3	Model 4
α	0,023	0,024		
	(0,004)	(0,004)		
β	0,840	-		
	(0,214)	-		
β^{EC}	-	0,925		
	-	(0,220)		
β^{TP}	-	-0,245		
	-	(0,234)		
γ	-	-		
	-	-		
δ	-			
	-			
Adj.-R^2	0,147	0,159		

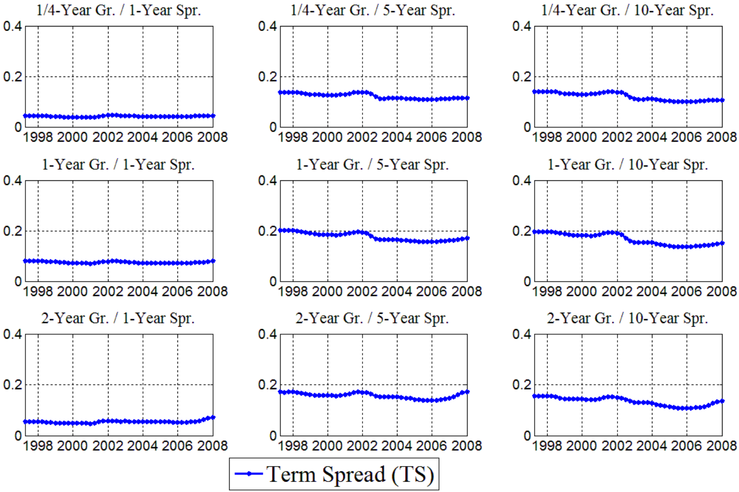
$$g_{t\rightarrow t+k} = \alpha_{k,m} + \beta^{EC}_{k,m}(Spr^{e,(k)}_t + \chi^{(k)}_t)) + \beta^{TP}_{k,m}\chi^{(k)}_t + \varepsilon_{k,m,t}$$

Table: Forecasting economic growth (1 year) using 5 yr spread

	Model 1	Model 2	Model 3	Model 4
α	0,023	0,024	0,025	0,029
	(0,004)	(0,004)	(0,010)	(0,012)
β	0,840	-	0,670	-
	(0,214)	-	(0,240)	-
β^{EC}	-	0,925	-	0,501
	-	(0,220)	-	(0,386)
β^{TP}	-	-0,245	-	0,136
	-	(0,234)	-	(0,359)
γ	-	-	0,150	0.149
	-	-	(0,068)	(0,070)
δ	-		-0,088	-0,159
	-		(0,115)	(0,170)
Adj.-R^2	0,147	0,159	0,199	0,199

$$g_{t\rightarrow t+k} = \alpha_{k,m} + \beta^{EC}_{k,m}(Spr^{e,(k)}_t + \chi^{(k)}_t)) + \beta^{TP}_{k,m}\chi^{(k)}_t + \gamma_{k,m}g_t + \delta_{k,m}y_t(1) + \varepsilon_{k,m,t}$$

Figure 5a: Forecasting real GDP growth, expanding window R-squared



Empirical analysis

Predicting changes in economic activity

Figure 5b: Forecasting real GDP growth, expanding window R-squared

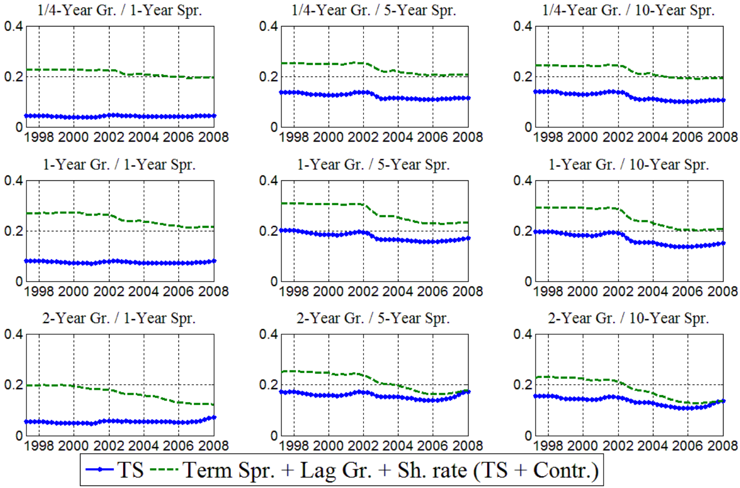
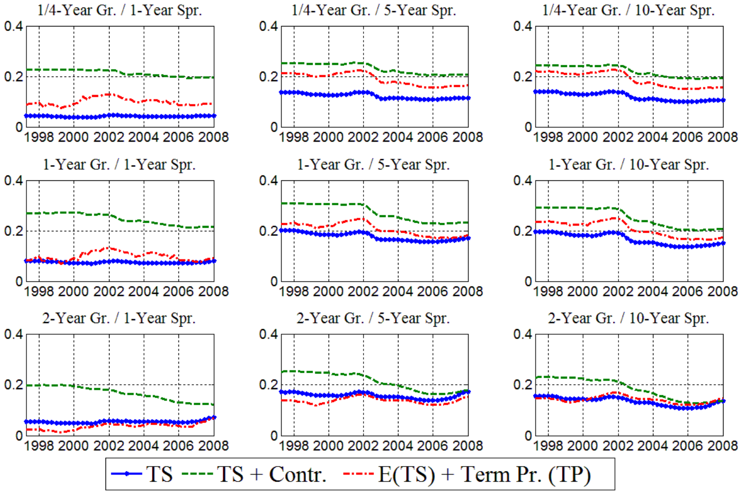


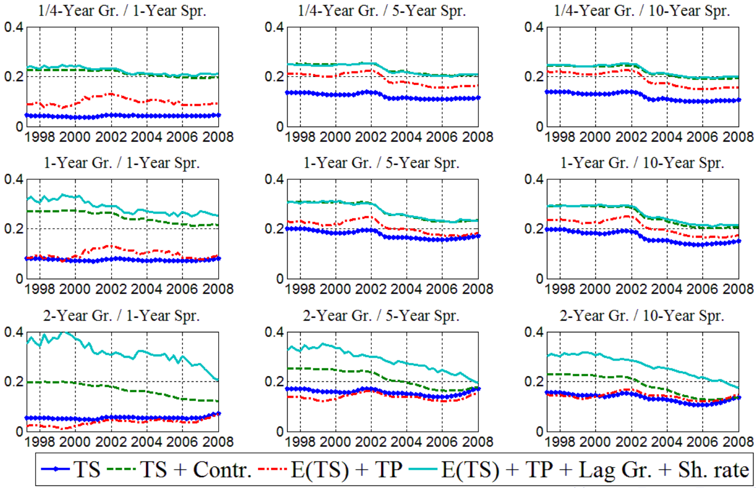
Figure 5c: Forecasting real GDP growth, expanding window R-squared



Empirical analysis

Predicting changes in economic activity

Figure 5d: Forecasting real GDP growth, expanding window R-squared



Predicting inflation changes

Base model. Inflation-change forecasting model of Mishkin (1990):

$$\pi_t^{(k)} - \pi_t^{(4)} = \alpha_k + \beta_k(Spr_t^{(k)})) + \varepsilon_{k,t}$$

$$\pi_t^{(k)} = \tfrac{4}{k}(\ln CPI_{t+k} - \ln CPI_t), \quad Spr_t^{(k)} = y_t(k) - y_t(4)$$

Alternative prediction regressions:

$$\pi_t^{(k)} - \pi_t^{(4)} = \alpha_k + \beta_k^{EC}(Spr_t^{e,(k)} + \chi_t^{(k)})) + \beta_k^{TP}\chi_t^{(k)} + \varepsilon_{k,t}$$

$$\pi_t^{(k)} - \pi_t^{(4)} = \alpha_k + \beta_k Spr_t^{(k)} + \gamma\pi_t^{(-4)} + \delta y_t^{(1)} + \varepsilon_{k,t}$$

$$\pi_t^{(k)} - \pi_t^{(4)} = \alpha_k + \beta_k^{EC}(Spr_t^{e,(k)} + \chi_t^{(k)})) + \beta_k^{TP}\chi_t^{(k)} + \gamma\pi_t^{(-4)} + \delta y_t^{(1)} + \varepsilon_{k,t}$$

Empirical analysis

Predicting changes in inflation

Table: FORECASTING CHANGES IN INFLATION: HORIZON 16 QTR

	Model 1	Model 2	Model 3	Model 4
α	-0,003			
	(0,002)			
β	0,622			
	(0,215)			
β^{EC}	-			
	-			
β^{TP}	-			
	-			
γ	-			
	-			
δ	-			
	-			
Adj.-R^2	0,155			

$$\pi_t^{(k)} - \pi_t^{(4)} = \alpha + \beta Spr_t^{(k)} + \varepsilon_{t+k}$$

Table: FORECASTING CHANGES IN INFLATION: HORIZON 16 QTR

	Model 1	Model 2	Model 3	Model 4
α	-0,003	-0,002		
	(0,002)	(0,002)		
β	0,622	-		
	(0,215)	-		
β^{EC}	-	0,895		
	-	(0,229)		
β^{TP}	-	-0,621		
	-	(0,132)		
γ	-	-		
	-	-		
δ	-			
	-			
Adj.-R^2	0,155	0,298		

$$\pi_t^{(k)} - \pi_t^{(4)} = \alpha + \beta^{EC}(Spr_t^{e,(k)} + \chi_t^{(k)}) + \beta^{TP}\chi_t^{(k)} + \varepsilon_{t+k}$$

Table: FORECASTING CHANGES IN INFLATION: HORIZON 16 QTR

	Model 1	Model 2	Model 3	Model 4
α	-0,003	-0,002	0,010	0,006
	(0,002)	(0,002)	(0,003)	(0,007)
β	0,622	-	0,246	-
	(0,215)	-	(0,183)	-
β^{EC}	-	0,895	-	1,071
	-	(0,229)	-	(0,307)
β^{TP}	-	-0,621	-	-1,233
	-	(0,132)	-	(0,363)
γ	-	-	-0,102	-0,280
	-	-	(0,084)	(0,078)
δ	-		-0,135	0,212
	-		(0,047)	(0,115)
Adj.-R^2	0,155	0,298	0,325	0,412

$$\pi_t^{(k)} - \pi_t^{(4)} = \alpha + \beta^{EC}(Spr_t^{e,(k)} + \chi_t^{(k)}) + \beta^{TP}\chi_t^{(k)} + \gamma\pi_t^{(-4)} + \delta y_t^{(1)} + \varepsilon_{t+k}$$

Empirical analysis

Predicting changes in inflation

Figure 6a: Forecasting inflation changes, expanding window R-squared

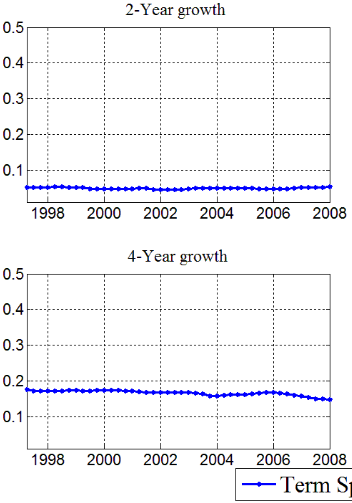


Figure 6b: Forecasting inflation changes, expanding window R-squared

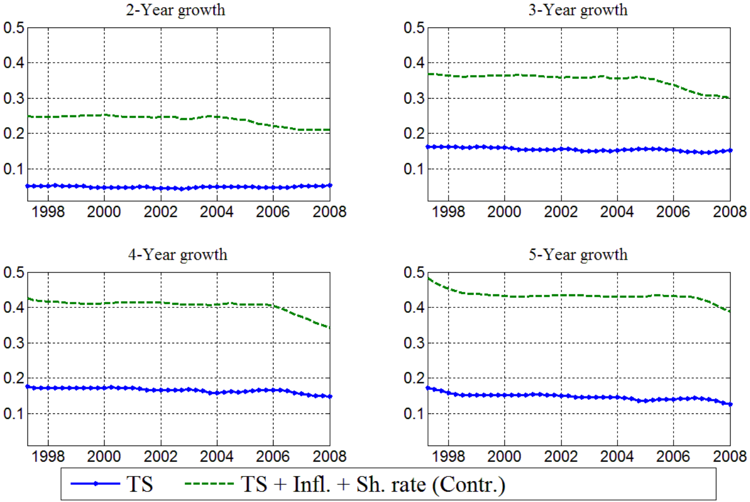


Figure 6c: Forecasting inflation changes, expanding window R-squared

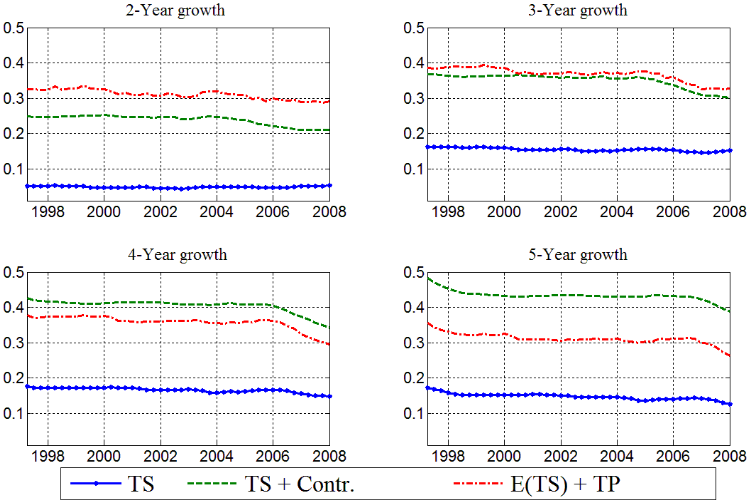
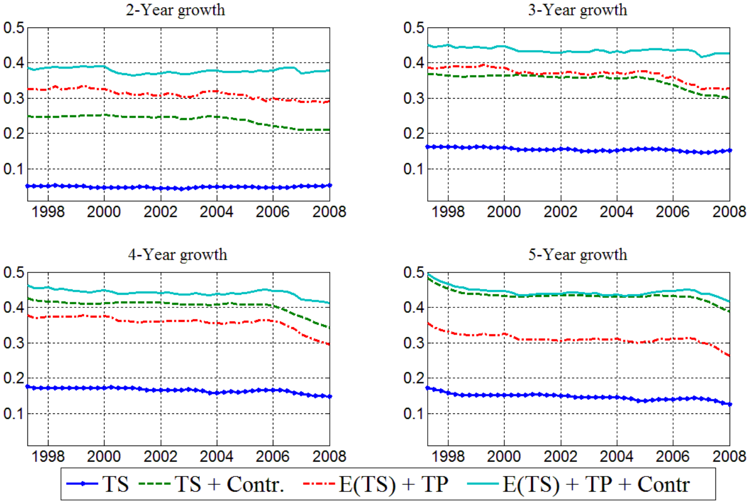


Figure 6d: Forecasting inflation changes, expanding window R-squared



Conclusion

- Model captures both macroeconomic and 'financial' drivers of the yield curve
- Financial and macroeconomic shocks impact differently on the yield curve:
    - Financial factors are dominant at high frequencies, macroeconomic factors more important at the lower frequencies
    - Financial factors dominate term premium factors while macroeconomic shocks dominate the expectations component
- Information in the (decomposed) yield curve?
    - Decomposition important for inflation change predictions (Mishkin (1990))
    - No strong evidence in favor of the decomposition for economic growth.
- Over time , a loss in predictive power of term spreads is observed.

Econometric Issues

Econometric issues

Summary: Bayesian estimation framework

Identification of the posterior density $p(\theta_i \mid Z^T)$ of the parameter vector θ :

$$p(\theta \mid Z^T) = L(Z^T \mid \theta)p(\theta)/p(Z^T)$$

with:

- $L(Z^T \mid \theta)$: the likelihood of the data, Z^T, given θ.
- $p(\theta)$: the prior density of the parameter vector, θ.
- $p(Z^T)$: the marginal likelihood of the data.

Bayesian techniques:

- Avoid estimation problems due to irregularities of the likelihood surface.
- Allow a broader analysis based on the posterior (instead of a local mode approx.).

Model is estimated on US data: 1960Q1 till 2008Q4.

- Quarter-by-quarter inflation (GDP deflator) rate (p.a. terms) are used. Source: Federal Reserve Economic Data archive (FRED).
- CBO output gap measure is used (no- real time data). Source: Congressional Budget Office.
- Fed fund rate is used as policy rate. Source FRED.
- LIBOR (US dollar) over the period 1986-2008. Source: BBA, British Bankers Association.
- Yield curve: 1/4, 1, 2, 3, 5, 10 yr. maturities. Source: Gürkaynak et al. (2006), CRSP, FRED.
- Inflation expectations: Average inflation expectations over 1 and 10 year horizon. Source: Survey of Professional Forecasters, FED Philadelphia.

Econometric issues

Data: statistical analysis

Preliminary statistical analysis provides evidence in favor of the extensions introduced in this paper:

- Unit root tests confirm the (near) I(1) behavior of various macroeconomic and financial variables:
  - Unit root test not rejected for inflation, yields and inflation expectations.
  - Unit root can be rejected for output gap, T-bill and LIBOR spreads.
- Cointegration analysis 'confirms' the presence of 2 stochastic trends in line with Joslin et al (2008), Giese (2008).
- Support for additional latent spread factors: Regression analysis shows that the spread factors are not fully spanned by macroeconomic factors:
  - LIBOR and TED spread only explained for 30% by macroeconomic factors.
  - T-bill spread explained for about 70%.

Variance decomposition yield

Table: VARIANCE DECOMPOSITION YIELDS

4-qtr yields

Hor.	Sup.sh.	Dem.sh.	Pol.r.sh.	Liq.sh.	Risk pr.sh.	LR inf.sh.	Eq. r.r.sh.
1Q	1,5%	1,1%	59,6%	22,5%	15,0%	0,3%	0,0%
2Q	1,4%	1,2%	61,8%	21,4%	13,7%	0,5%	0,1%
4Q	1,5%	1,4%	64,1%	20,1%	11,8%	1,0%	0,1%
10Q	1,5%	2,3%	62,9%	19,1%	9,6%	4,2%	0,4%
40Q	1,1%	2,1%	45,0%	15,2%	6,7%	27,1%	2,7%
100Q	0,7%	1,3%	28,4%	9,6%	4,3%	50,8%	4,9%

20-qtr yields

Hor.	Sup.sh.	Dem.sh.	Pol.r.sh.	Liq.sh.	Risk pr.sh.	LR inf.sh.	Eq. r.r.sh.
1Q	0,0%	0,1%	29,6%	13,9%	51,8%	4,3%	0,3%
2Q	0,1%	0,1%	34,5%	11,7%	48,0%	5,2%	0,4%
4Q	0,2%	0,1%	40,9%	9,4%	41,7%	7,2%	0,5%
10Q	0,2%	0,3%	43,5%	8,6%	31,9%	14,3%	1,2%
40Q	0,2%	0,5%	27,3%	5,7%	19,4%	42,9%	4,0%
100Q	0,1%	0,3%	15,8%	3,3%	11,2%	63,3%	6,0%

40-qtr yields

Hor.	Sup.sh.	Dem.sh.	Pol.r.sh.	Liq.sh.	Risk pr.sh.	LR inf.sh.	Eq. r.r.sh.

Table: Variance decomposition of expectation component

Expected average short-term rate over 4 quarters							
Hor.	Sup.sh.	Dem.sh.	Pol.r.sh.	Liq.sh.	Risk pr.sh.	LR inf.sh.	Eq. r.r.sh.
1Q	1,8%	1,4%	85,9%	10,5%	0,0%	0,2%	0,1%
2Q	2,6%	1,8%	83,9%	11,1%	0,0%	0,4%	0,1%
4Q	3,5%	2,7%	79,8%	12,8%	0,0%	1,0%	0,2%
10Q	3,7%	4,5%	68,7%	17,8%	0,0%	4,8%	0,6%
40Q	2,5%	3,5%	44,5%	15,8%	0,0%	30,6%	3,1%
100Q	1,5%	2,1%	26,4%	9,4%	0,0%	55,3%	5,4%

Expected average short-term rate over 20 quarters							
Hor.	Sup.sh.	Dem.sh.	Pol.r.sh.	Liq.sh.	Risk pr.sh.	LR inf.sh.	Eq. r.r.sh.
1Q	2,8%	5,2%	52,7%	24,6%	0,0%	13,2%	1,5%
2Q	3,0%	5,6%	48,2%	25,7%	0,0%	15,6%	1,8%
4Q	3,0%	6,0%	40,3%	27,4%	0,0%	20,8%	2,3%
10Q	2,2%	5,5%	25,2%	27,3%	0,0%	35,9%	3,8%
40Q	0,8%	2,1%	8,8%	11,9%	0,0%	69,5%	6,9%
100Q	0,4%	0,9%	3,7%	5,1%	0,0%	81,9%	8,0%

Expected average short-term rate over 40 quarters							
Hor.	Sup.sh.	Dem.sh.	Pol.r.sh.	Liq.sh.	Risk pr.sh.	LR inf.sh.	Eq. r.r.sh.
1Q	1,8%	3,1%	28,0%	18,3%	0,0%	44,2%	4,6%
2Q	1,8%	3,1%	24,4%	18,0%	0,0%	47,7%	5,0%
4Q	1,7%	3,0%	18,6%	17,2%	0,0%	53,9%	5,6%
10Q	1,1%	2,2%	9,7%	13,7%	0,0%	66,7%	6,8%
40Q	0,3%	0,6%	2,6%	4,5%	0,0%	83,8%	8,2%
100Q	0,1%	0,2%	1,0%	1,8%	0,0%	88,3%	8,5%

Table: Variance decomposition of term premium component

4-qtr term premium							
Hor.	Sup.sh.	Dem.sh.	Pol.r.sh.	Liq.sh.	Risk pr.sh.	LR inf.sh.	Eq. r.r.sh.
1Q	0,0%	0,0%	1,3%	25,3%	73,3%	0,1%	0,0%
2Q	0,7%	0,1%	0,9%	22,7%	75,6%	0,1%	0,0%
4Q	1,8%	0,5%	2,5%	18,6%	76,6%	0,1%	0,0%
10Q	2,0%	1,0%	10,6%	18,2%	68,0%	0,1%	0,0%
40Q	2,0%	1,0%	12,6%	21,2%	63,0%	0,2%	0,0%
100Q	2,0%	1,0%	12,6%	21,2%	63,0%	0,2%	0,0%

20-qtr term premium							
Hor.	Sup.sh.	Dem.sh.	Pol.r.sh.	Liq.sh.	Risk pr.sh.	LR inf.sh.	Eq. r.r.sh.
1Q	1,3%	0,8%	7,2%	3,4%	87,1%	0,2%	0,0%
2Q	2,2%	1,1%	11,5%	2,6%	82,3%	0,3%	0,0%
4Q	2,8%	1,4%	19,2%	5,1%	71,2%	0,3%	0,0%
10Q	2,4%	1,2%	27,0%	16,8%	52,2%	0,3%	0,0%
40Q	2,8%	1,2%	26,2%	22,4%	46,8%	0,6%	0,0%
100Q	2,8%	1,2%	26,2%	22,4%	46,8%	0,6%	0,0%

40-qtr term premium							
Hor.	Sup.sh.	Dem.sh.	Pol.r.sh.	Liq.sh.	Risk pr.sh.	LR inf.sh.	Eq. r.r.sh.
1Q	2,2%	0,6%	10,6%	1,3%	84,8%	0,5%	0,0%
2Q	3,2%	0,8%	14,7%	2,9%	77,9%	0,5%	0,0%
4Q	3,8%	0,9%	20,7%	8,8%	65,2%	0,6%	0,0%
10Q	3,5%	0,7%	24,8%	23,4%	46,9%	0,7%	0,0%
40Q	4,1%	0,8%	23,4%	29,3%	41,4%	1,0%	0,0%
100Q	4,1%	0,8%	23,4%	29,3%	41,4%	1,0%	0,0%

Table: VARIANCE DECOMPOSITION OF TERM SPREAD

4-qtr term spread

Hor.	Sup.sh.	Dem.sh.	Pol.r.sh.	Liq.sh.	Risk pr.sh.	LR inf.sh.	Eq. r.r.sh.
1Q	2,9%	0,2%	26,8%	18,5%	51,0%	0,6%	0,0%
2Q	2,1%	0,2%	25,6%	17,5%	53,8%	0,8%	0,0%
4Q	3,5%	0,4%	23,6%	14,9%	56,6%	1,1%	0,0%
10Q	4,8%	1,3%	20,8%	16,3%	55,4%	1,4%	0,0%
40Q	4,8%	1,3%	19,8%	21,1%	51,4%	1,5%	0,1%
100Q	4,8%	1,3%	19,8%	21,1%	51,4%	1,5%	0,1%

20-qtr term spread

Hor.	Sup.sh.	Dem.sh.	Pol.r.sh.	Liq.sh.	Risk pr.sh.	LR inf.sh.	Eq. r.r.sh.
1Q	0,2%	0,3%	47,9%	3,1%	45,3%	3,2%	0,2%
2Q	2,4%	0,7%	45,4%	2,7%	44,9%	3,7%	0,2%
4Q	5,8%	1,8%	40,2%	5,1%	42,6%	4,3%	0,2%
10Q	7,3%	3,3%	30,1%	20,0%	34,4%	4,7%	0,2%
40Q	6,9%	3,1%	25,9%	29,9%	29,3%	4,6%	0,2%
100Q	6,9%	3,1%	25,9%	29,9%	29,3%	4,6%	0,2%

40-qtr term spread

Hor.	Sup.sh.	Dem.sh.	Pol.r.sh.	Liq.sh.	Risk pr.sh.	LR inf.sh.	Eq. r.r.sh.
1Q	0,8%	0,7%	55,4%	3,8%	34,5%	4,5%	0,2%
2Q	3,3%	1,2%	51,8%	5,4%	33,0%	5,0%	0,3%
4Q	6,6%	2,3%	45,0%	10,9%	29,5%	5,6%	0,3%
10Q	7,8%	3,5%	32,7%	27,7%	22,3%	5,7%	0,3%
40Q	7,4%	3,3%	27,7%	37,0%	18,8%	5,5%	0,3%
100Q	7,4%	3,3%	27,8%	37,0%	18,8%	5,5%	0,3%

Table: Variance decomposition expec. comp. of term spread

			ex. component 4-qtr term spread				
Hor.	Sup.sh.	Dem.sh.	Pol.r.sh.	Liq.sh.	Risk pr.sh.	LR inf.sh.	Eq. r.r.sh.
1Q	12,1%	1,2%	78,9%	6,3%	0,0%	1,3%	0,2%
2Q	7,6%	1,0%	83,1%	6,5%	0,0%	1,6%	0,2%
4Q	5,5%	0,7%	85,7%	6,0%	0,0%	1,9%	0,2%
10Q	5,5%	0,8%	85,8%	5,5%	0,0%	2,2%	0,2%
40Q	5,4%	1,3%	84,1%	6,7%	0,0%	2,3%	0,2%
100Q	5,4%	1,3%	84,1%	6,7%	0,0%	2,3%	0,2%

			ex. component 20-qtr term spread				
Hor.	Sup.sh.	Dem.sh.	Pol.r.sh.	Liq.sh.	Risk pr.sh.	LR inf.sh.	Eq. r.r.sh.
1Q	0,2%	0,0%	91,5%	5,7%	0,0%	2,4%	0,2%
2Q	0,5%	0,0%	91,1%	5,6%	0,0%	2,6%	0,2%
4Q	1,6%	0,3%	89,8%	5,3%	0,0%	2,8%	0,2%
10Q	2,6%	1,3%	86,3%	6,5%	0,0%	3,1%	0,2%
40Q	2,5%	2,1%	83,0%	9,1%	0,0%	3,1%	0,2%
100Q	2,5%	2,1%	83,0%	9,1%	0,0%	3,1%	0,2%

			ex. component 40-qtr term spread				
Hor.	Sup.sh.	Dem.sh.	Pol.r.sh.	Liq.sh.	Risk pr.sh.	LR inf.sh.	Eq. r.r.sh.
1Q	0,0%	0,1%	90,0%	6,8%	0,0%	2,9%	0,2%
2Q	0,6%	0,3%	89,1%	6,8%	0,0%	3,0%	0,2%
4Q	1,7%	0,7%	87,1%	7,0%	0,0%	3,3%	0,2%
10Q	2,6%	2,2%	82,0%	9,4%	0,0%	3,6%	0,3%
40Q	2,6%	2,9%	77,9%	12,8%	0,0%	3,6%	0,3%
100Q	2,6%	2,9%	77,9%	12,8%	0,0%	3,6%	0,3%

Table: Variance decomposition yields

4-qtr yields

Hor.	Sup.sh.	Dem.sh.	Pol.r.sh.	Liq.sh.	Risk pr.sh.	LR inf.sh.	Eq. r.r.sh.
1Q	1,5%	1,1%	59,6%	22,5%	15,0%	0,3%	0,0%
2Q	1,4%	1,2%	61,8%	21,4%	13,7%	0,5%	0,1%
4Q	1,5%	1,4%	64,1%	20,1%	11,8%	1,0%	0,1%
10Q	1,5%	2,3%	62,9%	19,1%	9,6%	4,2%	0,4%
40Q	1,1%	2,1%	45,0%	15,2%	6,7%	27,1%	2,7%
100Q	0,7%	1,3%	28,4%	9,6%	4,3%	50,8%	4,9%

20-qtr yields

Hor.	Sup.sh.	Dem.sh.	Pol.r.sh.	Liq.sh.	Risk pr.sh.	LR inf.sh.	Eq. r.r.sh.
1Q	0,0%	0,1%	29,6%	13,9%	51,8%	4,3%	0,3%
2Q	0,1%	0,1%	34,5%	11,7%	48,0%	5,2%	0,4%
4Q	0,2%	0,1%	40,9%	9,4%	41,7%	7,2%	0,5%
10Q	0,2%	0,3%	43,5%	8,6%	31,9%	14,3%	1,2%
40Q	0,2%	0,5%	27,3%	5,7%	19,4%	42,9%	4,0%
100Q	0,1%	0,3%	15,8%	3,3%	11,2%	63,3%	6,0%

40-qtr yields

Hor.	Sup.sh.	Dem.sh.	Pol.r.sh.	Liq.sh.	Risk pr.sh.	LR inf.sh.	Eq. r.r.sh.
1Q	0,6%	0,0%	22,5%	4,8%	62,3%	9,2%	0,6%
2Q	1,0%	0,0%	26,6%	4,1%	56,8%	10,7%	0,8%
4Q	1,3%	0,0%	31,6%	5,0%	47,5%	13,6%	1,0%

Figure: Variance decomposition:Term Spread

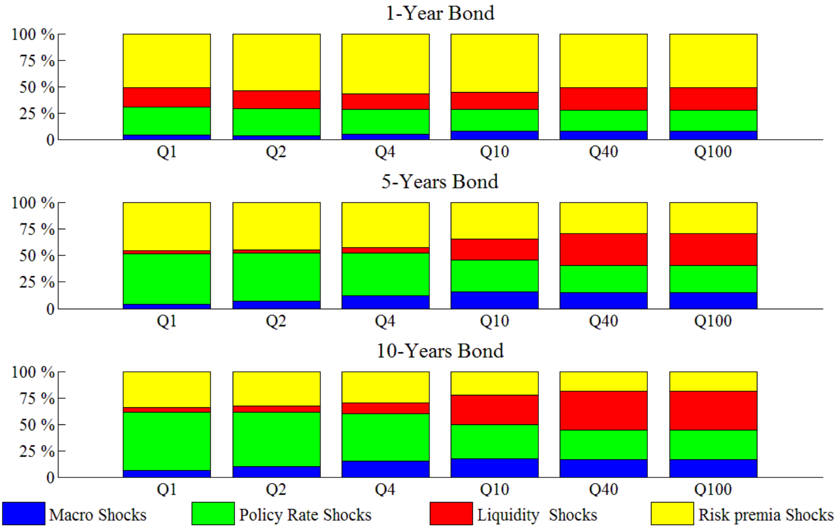


Figure: VARIANCE DECOMPOSITION:TERM PREMIUM

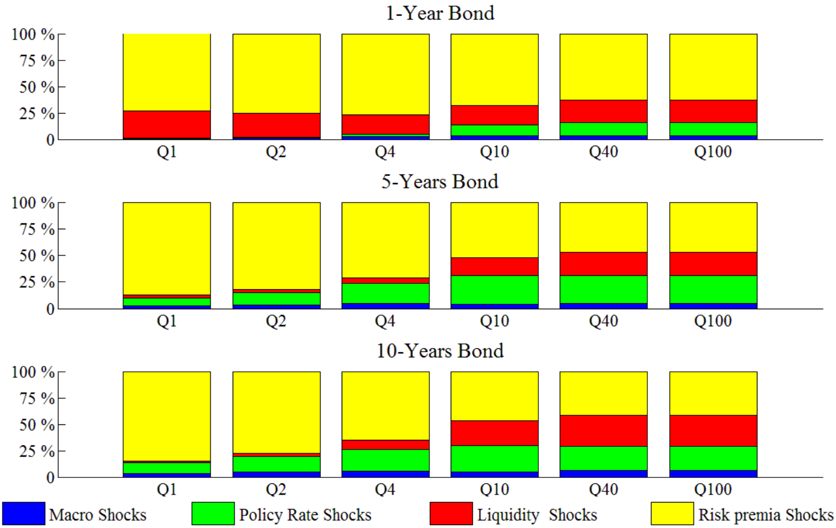


Figure: Variance decomposition:Expexted Component Term Spread

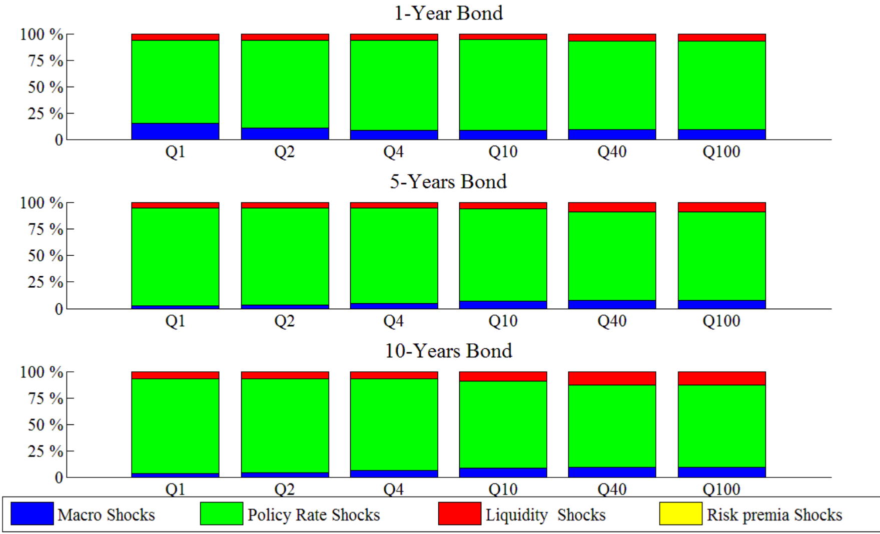


Table: FORECASTING REGRESSIONS: GDP GROWTH (1)

Model 1	$g_{t \to t+k} = \alpha + \beta Spr_t^{(n)} + \varepsilon_{t+k}$					
hor.(k)	1 qtr		4 qtr		8 qtr	
mat.(n)	4 qtr	40 qtr	4 qtr	40 qtr	4 qtr	40 qtr
β	1,362	0,593	1,462	0,583	1,090	0,455
	(0,469)	*(0,199)*	*(0,407)*	*(0,180)*	*(0,345)*	*(0,126)*
Adj.-R^2	0,044	0,076	0,078	0,110	0,072	0,113
Model 2	$g_{t \to t+k} = \alpha + \beta^{EC}(Spr_t^{e,(n)} + \chi_t^{(n)}) + \beta^{TP}\chi_t^{(n)} + \varepsilon_{t+k}$					
hor.(k)	1 qtr		4 qtr		8 qtr	
mat.(n)	4 qtr	40 qtr	4 qtr	40 qtr	4 qtr	40 qtr
β^{EC}	2,544	0,782	2,027	0,700	1,129	0,489
	(0,677)	*(0,205)*	*(0,654)*	*(0,184)*	*(0,597)*	*(0,127)*
β^{TP}	-1,198	-0,323	-0,705	-0,166	-0,083	0,042
	(0,733)	*(0,247)*	*(0,663)*	*(0,228)*	*(0,500)*	*(0,172)*
Adj.-R^2	0,097	0,118	0,108	0,143	0,093	0,142

Table: FORECASTING REGRESSIONS: GDP GROWTH (2)

Model 3	$g_{t\rightarrow t+k} = \alpha + \beta Spr_t^{(n)} + \gamma g_t + \delta y_t^{(1)} + \varepsilon_{t+k}$					
hor.(k)	1 qtr		4 qtr		8 qtr	
mat.(n)	4 qtr	40 qtr	4 qtr	40 qtr	4 qtr	40 qtr
β	1,158	0,389	1,290	0,434	0,992	0,410
	(0,417)	(0,193)	(0,393)	(0,205)	(0,343)	(0,187)
γ	0,269	0,260	0,169	0,159	0,047	0,038
	(0,084)	(0,084)	(0,069)	(0,070)	(0,051)	(0,052)
δ	-0,165	-0,095	-0,159	-0,081	-0,107	-0,028
	(0,103)	(0,122)	(0,100)	(0,128)	(0,085)	(0,112)
Adj.-R^2	0,184	0,175	0,182	0,165	0,103	0,111
Model 4	$g_{t\rightarrow t+k} = \alpha + \beta^{EC}(Spr_t^{e,(n)} + \chi_t^{(n)}) + \beta^{TP}\chi_t^{(n)} + \gamma g_t + \delta y_t^{(1)} + \varepsilon_{t+k}$					
hor.(k)	1 qtr		4 qtr		8 qtr	
mat.(n)	4 qtr	40 qtr	4 qtr	40 qtr	4 qtr	40 qtr
β^{EC}	0,671	0,615	0,023	0,412	-0,439	0,217
	(0,898)	(0,273)	(0,973)	(0,319)	(0,971)	(0,353)
β^{TP}	0,536	-0,195	1,258	0,107	1,531	0,321
	(0,866)	(0,280)	(0,901)	(0,321)	(0,822)	(0,336)
γ	0,248	0,241	0,156	0,152	0,043	0,040
	(0,082)	(0,087)	(0,064)	(0,071)	(0,041)	(0,048)
δ	-0,262	-0,005	-0,344	-0,124	-0,316	-0,162
	(0,130)	(0,144)	(0,138)	(0,176)	(0,114)	(0,186)
Adj.-R^2	0,201	0,188	0,221	0,183	0,193	0,153

Table: FORECASTING CHANGES IN INFLATION (1)

Model 1	$\pi_t^{(k)} - \pi_t^{(4)} = \alpha + \beta Spr_t^{(k)} + \varepsilon_{t+k}$			
k	8 qtr	12 qtr	16 qtr	20 qtr
α	-0,001	-0,002	-0,003	-0,003
	(0,001)	(0,002)	(0,002)	(0,003)
β	0,419	0,655	0,622	0,516
	(0,203)	(0,208)	(0,215)	(0,236)
Adj.-R^2	0,063	0,161	0,155	0,113
Model 2	$\pi_t^{(k)} - \pi_t^{(4)} = \alpha + \beta^{EC}(Spr_t^{e,(k)} + \chi_t^{(k)}) + \beta^{TP}\chi_t^{(k)} + \varepsilon_{t+k}$			
k	8 qtr	12 qtr	16 qtr	20 qtr
α	-0,001	-0,001	-0,002	-0,001
	(0,001)	(0,001)	(0,002)	(0,003)
β^{EC}	1,045	1,022	0,895	0,727
	(0,239)	(0,228)	(0,229)	(0,249)
β^{TP}	-0,718	-0,693	-0,621	-0,572
	(0,157)	(0,144)	(0,132)	(0,144)
Adj.-R^2	0,302	0,343	0,298	0,233

Table: FORECASTING CHANGES IN INFLATION (2)

Model 3	$\pi_t^{(k)} - \pi_t^{(4)} = \alpha + \beta_t Spr_t^{(k)} + \gamma \pi_t^{(-4)} + \delta y_t^{(1)} + \varepsilon_{t+k}$			
k	8 qtr	12 qtr	16 qtr	20 qtr
α	0,004	0,007	0,010	0,015
	(0,002)	(0,003)	(0,003)	(0,004)
β	0,253	0,353	0,246	0,054
	(0,167)	(0,183)	(0,183)	(0,179)
γ	-0,012	-0,044	-0,102	-0,170
	(0,056)	(0,076)	(0,084)	(0,087)
δ	-0,075	-0,116	-0,135	-0,153
	(0,027)	(0,039)	(0,047)	(0,053)
Adj.-R^2	0,193	0,300	0,325	0,347
Model 4	$\pi_t^{(k)} - \pi_t^{(4)} = \alpha + \beta^{EC}(Spr_t^{e,(k)} + \chi_t^{(k)}) + \beta^{TP}\chi_t^{(k)} + \gamma \pi_t^{(-4)} + \delta y_t^{(1)} + \varepsilon_{t+k}$			
k	8 qtr	12 qtr	16 qtr	20 qtr
α	-0,005	-0,005	-0,001	0,006
	(0,002)	(0,003)	(0,005)	(0,007)
β^{EC}	1,707	1,450	1,071	0,603
	(0,371)	(0,289)	(0,307)	(0,329)
β^{TP}	-1,713	-1,516	-1,233	-0,904
	(0,384)	(0,311)	(0,363)	(0,412)
γ	-0,137	-0,225	-0,280	-0,318
	(0,051)	(0,062)	(0,078)	(0,090)
δ	0,172	0,232	0,212	0,128