International Review of Financial Analysis 84 (2022) 102355

Contents lists available at ScienceDirect

International Review of Financial Analysis

journal homepage: www.elsevier.com/locate/irfa

Term premium dynamics in an emerging market: Risk, liquidity, and behavioral factors☆

Cenk C. Karahan [a,*], Emre Soykök [b]

[a] Department of Management, Bogazici University, Istanbul, 34342, Turkey
[b] Naveen Jindal School of Management, The University of Texas at Dallas, Richardson, TX, 75080, USA

ARTICLE INFO

JEL classification:
E43
E71
G12
G41

Keywords:
Term premium
Behavioral finance
Risk
Liquidity
Ambiguity

ABSTRACT

This paper contributes to the fixed income research by identifying determinants of term premium in an emerging market's treasury bond yields with particular attention on ambiguity. We use Nelson–Siegel yield curves generated from daily bond price quotes as input to construct a three-factor affine term structure model which decomposes observed yields into risk-neutral and term premium components. We also construct an ambiguity index using intraday FX return data following Brenner and Izhakian (2018). Our analyses suggest that a combination of factors representing market risk, credit risk, liquidity, ambiguity, and investor sentiments can explain majority of the variation in term premia. Explanatory power of credit risk measures are found to increase while those of volatility, ambiguity, and sentiment measures diminish with the maturity horizon. The results imply that ambiguity aversion of bond investors is a major determinant of the shape of the yield curve as it drives the premia for short end of the yield curve lower in line with the expectation of flight-to-safety behavior.

1. Introduction

Sovereign bond yields are one of the fundamental indicators that investors use as benchmark for other interest rates and draw inferences regarding future situation of the economy. Early interpretation of the relationship between term to maturity and bond yields depended on the expectations hypothesis which is credited to Fisher, Hicks, and Lutz (Wood, 1964). The expectation hypothesis proposes that long-term interest rates reflect expected future short-term interest rates except a possible constant liquidity preference premium. Then, return on investing in a long-term bond would be equal to expected return on investing the same amount on a short-term bond and rolling over this investment until the maturity of the long-term bond. Despite simplicity of the hypothesis, usual arbitrage arguments cannot show the equivalence of these two investments even though default risk and convexity[1] adjustment are disregarded. That is because at any point in time, possibly until the last rolling period, investment in a long-term bond has greater duration than that in a short-term bond, thus greater exposure to interest rate risk. Risk-averse investors would demand compensation for bearing any such risk.

Accordingly, researchers documented that holding returns on investing in long-term bonds over short-term bonds have a time-varying forecastable component suggesting that investors demand a premium as compensation for interest rate risk they bear. Contrary to the expectations hypothesis, term structure models allowing this compensation to exist differentiate observed yield curves from risk-neutral yield curves by time-varying term premia. A growing body of research since Fama (1984) aimed to understand time-variation in term premium. Earlier works in the field such as Campbell and Shiller (1991), Cochrane

☆ Emre Soykök, who coauthored this study, has unexpectedly passed away shortly after the completion of the manuscript. This paper is dedicated to his memory.

* Corresponding author.
E-mail addresses: cenk.karahan@boun.edu.tr (C.C. Karahan), emre.soykok@utdallas.edu (E. Soykök).

[1] It should be noted that instantaneous forward rates derived from bond prices should differ from expected future short rates even if investors are assumed to be risk-neutral. Gilles (1996) gives an arbitrage opportunity for the contrary case with two possible states of the world. The general case follows from the fact that bond price is a convex function of short rates which together with the Jensen's inequality indicate that instantaneous forward rates always underestimate expected future short rates when investors are risk-neutral. This convexity effect is proportional to the volatility of short rate. Some term structure models include a convexity adjustment in term premium whereas others only count pure term premium which stems from risk aversion of investors. As the effect of convexity adjustment is negligible for bonds with a maturity up to 20 years (Gurkaynak, Sack, & Wright, 2007), two definitions generate highly collinear term premia estimates.

https://doi.org/10.1016/j.irfa.2022.102355
Received 30 January 2022; Received in revised form 18 July 2022; Accepted 30 August 2022
Available online 5 September 2022
1057-5219/

and Piazzesi (2005), Dai and Singleton (2002), Duffee (2002), Fama and Bliss (1987) and Hardouvelis (1994) remarked the relationship between term premium and the yield curve components. More recent contributions investigated how macroeconomic factors are related to the term premium. These factors include variables such as unemployment gap (Li, Meldrum, & Rodriguez, 2017), expected inflation (Duffee, 2018), GDP and labor force growth (Bauer & Rudebusch, 2020), government spending (Bretscher, Hsu, & Tamoni, 2020), public debt (Nguyen, 2021), credit risk (Solis, 2021), and market volatility (Mallick, Mohanty, & Zampolli, 2017).

As our understanding of financial decision-making extended beyond risk, the literature on determinants of term premia incorporated new factors. The most notable contribution of the study at hand is use of ambiguity in financial markets to explain interest rate behavior. We hypothesize that the term premia, hence the shape of the yield curve, are impacted by the level of ambiguity in the market and the behavior of ambiguity averse investors. The literature on the issue is garnering more attention in recent years. However, existing studies are limited to ambiguity or Knightian uncertainty on macroeconomic factors such as inflation uncertainty (Breach, D'Amico, & Orphanides, 2020; Wright, 2011), inflation ambiguity (Zhao, 2020), disagreements in future bond yield forecasts (Giacoletti, Laursen, & Singleton, 2021) and economic policy uncertainty (EPU) (Leippold & Matthys, 2022). These variables are mostly on monthly frequency US data and rely on analyst estimates or partly on news coverage as in EPU's case.

This study contributes to the topic by documenting the impact of market ambiguity on term premia, while controlling for factors such as market risk, credit risk and liquidity along with sentiment. The test case Turkey is one of the largest and internationally connected emerging markets. Turkey's bond market is centralized via trading in Borsa İstanbul, which was in the top 10 in the world and top 5 in EMEA region in terms of bond trading volume during the study period.[2] The central nature of the bond market and availability of ample data allows us to document liquidity of the market in a reliable manner. Furthermore, we introduce an ambiguity measure, which is estimated from volatility of return probabilities pertaining to the intraday FX market following Brenner and Izhakian (2018), as one of term premium determinants.[3] Unlike previous macroeconomic proxies for ambiguity or uncertainty, this is a measure directly estimated from high frequency FX market data on a daily basis. The source and frequency of the data allows us to gauge the impact of ambiguity on a granular level with daily impact. We conjecture that the financial markets carry timely information thus offer more explanatory power than macroeconomic data. To the best of our knowledge, this will be the first study using this novel ambiguity measure in explaining interest rates in any market. We hope this paper paves the way for further studies documenting ambiguity's impact on interest rates in other emerging markets as well as developed ones.

2. Literature review

Earlier works testing the expectations hypothesis relied on treasury bills due to the lack of an appropriate term structure model. Fama (1984) argued that yields peak at 8 months instead of monotonically increasing towards 12 months and the term spread, namely the slope of yield curve, can forecast excess holding period returns on bonds. He asserted that these observations are inconsistent with both expectations hypothesis and liquidity preference hypothesis. In one of the first works suggesting long-term yields be composed of expectation and term premium components, Fama and Bliss (1987) regressed the difference between one-year spot rates at various horizons on forward-spot spread. They found that forward-spot spread can forecast the change in one-year spot rates and the prediction power of this forecast increases with time to maturity. The authors claimed that long-term bond prices have a risk component which vary through time. Campbell and Shiller (1991) tested the expectations hypothesis by regressing excess holding period returns on term spreads for various times to maturity up to 10 years. They claimed that for almost any two times to maturity, high term spread predicts a declining yield for long-term bond through the life of short-term bond. They argued that this observation indicates a deviation from the expectations hypothesis, possibly resulting from time-varying risk premia in bond yields.

A large strand of literature followed these initial efforts to document the relationship between term premia and yield curve components. Hardouvelis (1994) argued that widened term spread predicts declining long-term bond yields for most of the Group of Seven countries. Gurkaynak and Wright (2012) asserted that expectations hypothesis tests generally result in strong rejection for observation periods with high inflation uncertainty or countries where central banks stabilized interest rates. Duffee (2002) claimed that affine term structure models produce poor forecasts because model framework is unable to reflect aberrations from expectations hypothesis. He proposed a model where the term premium component could vary independently of the yield volatility. Similarly, Dai and Singleton (2002) suggested that affine term structure models could incorporate deviations from the expectation hypothesis if risk factors are parameterized to determine market prices of risk directly. Cochrane and Piazzesi (2005, 2009) extended the affine term structure models up to four factors to explain the variation in term premia. Joslin, Singleton, and Zhu (JSZ, 2011) proposed a model with observed yields as state variables imposing no-arbitrage condition. Similarly, Joslin and Le (2021) contended that no-arbitrage condition in affine term structure models affects yield forecasts and volatility dynamics only when interest rate volatility is assumed to be stochastic.

In addition to yield curve factors, several studies included macroeconomic factors as state variables in affine term structure models. Ang and Piazzesi (2003) attributed a significant portion of the explanatory power of inflation and economic growth factors in yields to their correlations with level and slope components. In compliance with general equilibrium asset pricing perspective, Wright (2011) regressed term premia estimates on inflation uncertainty measures for 10 developed countries and reported a strong positive relationship explaining a substantial part of term premia. Joslin, Priebsch, and Singleton (2014) used an affine term structure model which includes macroeconomic factors that are unspanned by yield curve factors to estimate their predictive power on excess bond returns finding again that inflation risk has a crucial impact on term premia. De Graeve, Emiris, and Wouters (2009) proposed a more structured dynamic stochastic equilibrium model to estimate term premium and future interest rate expectations of investors dependent on eight exogenous processes, each describing a macroeconomic factor such as aggregate demand or government spending. Authors claimed that resulting interest rate expectation component can explain approximately 90% of fluctuations in yields, indicating that the need for a time-varying risk premium may be lower than expected. Kim and Orphanides (2012) proposed incorporating forecasting surveys as an additional input to affine term structure models and claimed that this would result in a more reasonable and stable estimation of long-horizon term structure dynamics.

Adrian, Crump, and Moench (ACM, 2013) proposed an affine term structure model which uses principal components of yields as state variables to price interest rate risk using computationally fast three-step linear regressions to estimate all parameters. This practical and

[2] Source: The World Federation of Exchanges (WFE). https://www.world-exchanges.org.

[3] Since intraday data on bond prices and interest rates are unavailable or unreliable due to sparse trading, we use exchange rate against the US dollar to proxy risk and ambiguity of bond markets and wider economy. Turkey as an emerging market affords us to make that connection with certain confidence as Hofmann, Shim, and Shin (2020) argue that in emerging market economies, currency appreciation against the US dollar goes hand in hand even with local currency sovereign bond yields.

effective model, which has become one of the standard methods in the literature, is the methodological guide of our study in term premia estimation. They allowed each factor to contribute to market prices of risk, thus adapting to various risk specifications that the shape of yield curve may imply. Risk-neutral coefficients in the VAR specification of factors are found by taking one-month yields as risk-free rates, while risk prices are identified by regressing monthly excess holding returns on long-term bonds on lagged factors and contemporaneous factor innovations. Their model also adjusts yields derived from bond prices for convexity, and therefore estimates pure term premium. Authors asserted that their model has superior forecasting performance compared to four-factor model of Cochrane and Piazzesi (2009), while two models are equally successful in explaining in sample term premia dynamics.

The literature on the local term premia dynamics and determinants offer a few recent examples. Aydin and Ozel (2019) estimated monthly time series of term premia in Turkish treasury yields between May 2005 and February 2019 by using both ACM and JSZ models. They asserted that both models generate similar term premium estimates with a correlation coefficient as high as 0.99 and fit the yield curve well. They also claimed that future interest rate estimates derived from affine models trace market conditions more intimately than expectation surveys which tend to stay flat and react to changing conditions after a time lag. They remarked the countercyclical behavior of term premium and attributed a significant portion of its variance to foreign holdings in treasury bond market. Adopting the ACM framework, Ozbek and Talaslı (2020) estimated monthly time series of term premia in treasury yields between January 2010 and October 2018 for 16 emerging markets including Turkey. They asserted that market-wide liquidity and foreign exchange volatility are significant determinants of term premia while inflation and economic surprise indices are positively correlated with it. However, authors did not share information about portion of variance explained by these factors. Akgiray, Baronyan, Sener, and Yılmaz (2016) and Cepni and Güney (2019) explain emerging market term premia by data mining multitude of macroeconomic and financial factors with explanatory power of their factors ranging from 24 to 55%.

Since the seminal introduction of the concept by Knight (1921), Knightian uncertainty or ambiguity has been incorporated into economic and financial decision making as a factor distinct from risk.[4] The limited number of studies on ambiguity and interest rates focus mostly on theoretical models and ambiguity on macroeconomic variables such as inflation. In one of the earlier works in the field, Gagliardini, Porchia, and Trojani (2009) modeled a utility function based on ambiguity aversion and documented how excess bond returns reflect a premium for ambiguity on top of the risk premium. Ulrich (2013) documented inflation ambiguity and its impact on term structure of interest rates in the US bond market. Wright (2011) uses dispersion of forecasts on one-year ahead inflation and GDP as proxies for uncertainty to document their positive impact on longer term premia in a panel data of developed countries. In a more recent study, Zhao (2020) offered an equilibrium bond pricing model using ambiguity about inflation and growth to explain the nominal and real bond returns. Breach et al. (2020) used a survey-based inflation uncertainty to document its impact in a novel quadratic term structure model. Giacoletti et al. (2021) used dispersion in bond yield forecasts as a proxy for ambiguity and documented its varying impact on bond premia across maturities. Most recently, Leippold and Matthys (2022) took economic policy uncertainty (EPU) index by Baker, Bloom, and Davis (2016) as input to document its impact in a general equilibrium model populated by uncertainty averse investors. They claimed that not only bond risk premia carry a premium for political uncertainty, shorter maturities show a distinct flight-to-quality when the uncertainty is heightened.

[4] We refer the interested reader to Guidolin and Rinaldi (2013) and references therein for a survey on the asset pricing implications of ambiguity.

Table 1
Summary statistics of treasury bonds.

Daily observation	Mean	St. Dev.	Min	Max
Panel A. 2812 trading days between 27.01.2010 and 31.03.2021				
Number of bonds	22.37	3.67	9	32
Number of discount bonds	5.12	3.4	0	15
Number of coupon bonds	17.25	5.78	2	27
Average years to maturity	2.97	0.75	1.05	4.41
Highest years to maturity	9.28	0.73	4.27	10
Average duration	2.32	0.53	0.97	3.38
Highest duration	6.04	0.62	3.45	7.32
Panel B. 1273 trading days between 06.01.2005 and 26.01.2010				
Number of bonds	19.62	2.53	14	26
Number of discount bonds	16.89	3.18	12	23
Number of coupon bonds	2.73	1.07	0	6
Average years to maturity	0.97	0.24	0.53	1.43
Highest years to maturity	3.97	1.05	1.49	5
Average duration	0.87	0.19	0.53	1.28
Highest duration	2.98	0.68	1.49	3.98

Notes: This table shows summary statistics for treasury bonds traded between 6 January 2005 and 31 March 2021.

3. Data

The historical price data of all bonds traded on Borsa Istanbul (BIST) for all trading days between 6 January 2005 and 31 March 2021 is the major input for this study. BIST Data Platform publishes a daily bulletin on its website with historical data on all bonds available to trade on a given day.[5] We eliminate corporate bonds, bonds denominated in a foreign currency, stripped from their coupons or principals, floating rate bonds and inflation-indexed bonds. As a result, the remaining is the data of all discount and fixed coupon-bearing Turkish treasury bonds. For every trading day in the observation period, it displays weighted average prices, accrued coupons, times to maturity, and time to the next coupon payments. Day count convention in Turkish treasury market is 364 days, therefore semi-annual and quarterly coupons are paid respectively once in every 182 and 91 days. We calculate cash flows amounts and times for all bonds using these raw quotes. Observation period includes a total of 4085 trading days.

An important point to mention is that 10-year treasury bonds were first issued on 27 January 2010. Thus, the highest time to maturity for a bond was 5 years before this date. Table 1 reports summary statistics before and after the issuance of 10-year bonds, as this date acts as a break in the market in terms of the composition of instruments. Number of bonds traded each day varied between 9 and 32 across the entire period. However as can be seen in the two separate panels in Table 1, while discount bonds were the predominant type of instrument before 2010, coupon-bonds dominated the market after 2010. Introduction of 10-year bonds also changed average times to maturity of bonds traded each day. While mean of this figure was approximately 1 year before January 2010, later it tripled to approximately 3 years. Meanwhile, corresponding impact was slightly weaker in average duration of bonds traded each day with mean figures jumping from 0.87 years to 2.32 years.

4. Methodology

We use the model in Nelson and Siegel (1987) to extract yield curves from prices of treasury bonds. This choice can be tracked back to reasons making Nelson–Siegel yields a suitable input to construct more complex no-arbitrage affine term structure models. Firstly, yield curve is represented by a smooth continuous function that extrapolates reasonably well towards the long end of the curve after the maximum time

[5] Source: Borsa Istanbul Debt Securities Market Data. https://www.borsaistanbul.com.

to maturity of bonds of which prices it fits. Secondly, Laguerre functions are sufficiently flexible to approximate various shapes forward curve takes during the period they will be fitted. Finally, Nelson–Siegel results are documented to fit better than more sophisticated models when tested in most markets including Turkey.

In the Nelson–Siegel and Diebold-Li models, the proposed specifications for instantaneous forward curve and yield curve result in equal yields. We choose the factorization of Diebold and Li (2006) since estimated parameters are more intuitive in the latter. To put it another way, the instantaneous forward rate is expressed as:

$$f^{NS}(m) = \beta_1 + \beta_2 e^{-\lambda m} + \beta_3 \lambda m e^{-\lambda m} \tag{1}$$

where β_1, β_2, β_3, and λ are Nelson–Siegel parameters with λ being positive. The corresponding yield curve can be represented as:

$$y^{NS}(m) = \beta_1 + \beta_2 \left(\frac{1 - e^{-\lambda m}}{\lambda m}\right) + \beta_3 \left(\frac{1 - e^{-\lambda m}}{\lambda m} - e^{-\lambda m}\right) \tag{2}$$

Nelson–Siegel parameters can be estimated using non-linear least squares optimization.[6]

Recent literature provided evidence which demonstrates fitting errors in the Nelson–Siegel model contain valuable information on financial markets. When a shock to bond prices cannot be absorbed by arbitrage capital in the market, fitting errors stay high for a series of days or even months. That is to say, insufficient trade volumes in bond market make room for arbitrage opportunities. Following Hu, Pan, and Wang (2013), we define a market-wide illiquidity measure which tracks episodes of liquidity crises as mean root square yield error of bonds with times to maturity longer than 1-year. Since yields on coupon-bearing bonds are not observed, we define Nelson–Siegel yield to maturity of a bond as y^{NS}_{ytm} which is a constant interest rate resulting in the bond's Nelson–Siegel price:

$$P^{NS}_{C,M} = \sum_{i=1}^{T} c_i e^{\left(-m_i y^{NS}_{ytm}\right)} \tag{3}$$

Next, comparing the yield-to-maturity of bond k on day t implied by the market price, $y_{ytm,k}$, to that implied by Nelson–Siegel model, $y^{NS}_{ytm,k}$, market illiquidity on day t is defined as:

$$\text{Illiquidity}_t = \sqrt{\frac{\sum_{k=1}^{l_t} \left(y_{ytm,k} - y^{NS}_{ytm,k}\right)^2}{l_t}} \tag{4}$$

where l_t denotes the number of bonds with times to maturity longer than 1-year traded on day t. Karahan and Soykok (2022) compared this daily noise measure with other proxies for bond market illiquidity and reported its capability of representing market wide illiquidity .

4.1. Term premia estimation

We implement the ACM model which requires using Nelson Siegel yields as input to estimate term premium in Turkish treasury yield curve. However, using only yield curve factors does not restrict model's capability to generate economic interpretation since estimated term premium can then be regressed on macroeconomic factors (Wright, 2011), which is the aim of this study.

Assume term premium on a short period is negligible for simplicity. Then, term premium on n-period yield at date t is tp^t_n which satisfies:

$$y^t_n = \frac{1}{n} E_t \left(\sum_{i=0}^{n-1} r^{t+i}\right) + tp^t_n \tag{5}$$

where r^t denotes the risk-free interest rate for a short period and E_t denotes expectation taken according to the information set in t. The first term on the right-hand side accounts for expected return on rolling over one-period discount bonds for the next n periods, with the first term in the summation being only observed rate. The second term is the interest rate risk premium component in n-period yield which is in excess of the average expected one-period rates. It is beneficial to denote the term premium using excess holding period returns on bonds. To do this, first define one-period holding return on n-period discount bond as the ex-post realized return on buying an n-period discount bond at date t and selling it after a short period as an $n-1$ period discount bond:

$$r^{t+1}_{n-1} = lnP^{t+1}_{n-1} - lnP^t_n \tag{6}$$

One-period excess holding return on n-period discount bond is the difference between one-period holding return on n-period discount bond and return on investing in a one-period discount bond:

$$rx^{t+1}_{n-1} = r^{t+1}_{n-1} - r^t \tag{7}$$

Then, using Eqs. (5) and (7), n-period term premium is defined as the average of expected one-period excess holding returns of declining times to maturity for the next $n-1$ periods:

$$tp^t_n = \frac{1}{n-1} E_t \left(\sum_{i=1}^{n-1} rx^{t+i}_{n-i}\right) \tag{8}$$

For estimation purposes, effective size of samples increases with expressing term premium as excess holding period returns on bonds since short holding periods diminish the hindrance of overlapping observations (Kim & Orphanides, 2007).

Under the affine term structure framework, series of assumptions are made to ensure that yields are affine functions of state variables as in Duffee (2002). Dynamics of K state variables are assumed to follow a $VAR(1)$ model under both physical and risk-neutral probability measures with normally distributed shocks and common variance covariance matrix Σ. Thus, physical evolution of state variables is given by:

$$X_{t+1} = \mu + \phi X_t + \upsilon_{t+1} \tag{9}$$

Similarly, risk-neutral evolution is given by:

$$X_{t+1} = \tilde{\mu} + \tilde{\phi} X_t + \tilde{\upsilon}_{t+1} \tag{10}$$

where $\mu, \tilde{\mu}, \upsilon, \tilde{\upsilon}$, and X_t are $K \times 1$ matrices while ϕ and $\tilde{\phi}$ are $K \times K$ matrices. Therefore, time-varying market prices of risk are also linear in state variables:

$$\lambda_t = \Sigma^{-\frac{1}{2}} \left(\lambda_0 + \lambda_1 X_t\right) \tag{11}$$

where transition between physical and risk-neutral measures are defined by parameters $\lambda_0 = \Sigma^{-\frac{1}{2}}(\mu - \tilde{\mu})$ and $\lambda_1 = \Sigma^{-\frac{1}{2}}(\phi - \tilde{\phi})$. Risk-free interest rate is assumed to be linear in state variables:

$$r_t = \delta_0 + \delta_1' X_t \tag{12}$$

where δ_0 is a constant and δ_1 is a $K \times 1$ matrix. Imposing no-arbitrage condition indicates the existence of a stochastic discount factor M which consistently prices bonds:

$$P^t_n = E_t \left(M_{t+1} P^{t+1}_{n-1}\right) \tag{13}$$

Eqs. (9) and (12) imply that stochastic discount factor is exponentially affine and lognormally distributed:

$$M_{t+1} = e^{-r_t - \frac{1}{2}\lambda_t' \lambda_t - \lambda_t' \Sigma^{-\frac{1}{2}} \upsilon_{t+1}} \tag{14}$$

Assuming excess holding period returns $rx^{(t+1)}_{(n-1)}$ and shocks to the state variables $\upsilon_{(t+1)}$ are jointly normally distributed and using Eqs. (7), (11), (13), and (14), Adrian et al. (2013) found that unexpected excess

[6] Due to a local minima problem that non-linear least squares algorithm suffers, we fix λ with its optimum value $\hat{\lambda}$ which conditions loading of curvature component to peak at 2.28 years. This replacement switches the optimization problem into a linear one.

holding period return can be decomposed into a component correlated with $v_{(t+1)}$ and another that is orthogonal:

$$rx_{n-1}^{t+1} - E_t\left(rx_{n-1}^{t+1}\right) = \beta'_{n-1} v_{t+1} + e_{n-1}^{t+1} \tag{15}$$

where $\beta'_{n-1} = \mathrm{Cov}_t\left(rx_{n-1}^{t+1}, v'_{t+1}\right)\Sigma^{-1}$ is a $1 \times K$ matrix and e_{n-1}^{t+1} denotes the return pricing error with variance σ^2. Then, excess holding period returns can be decomposed into four components:

$$rx_{n-1}^{t+1} = \beta'_{n-1}\left(\lambda_0 + \lambda_1 X_t\right) - \frac{1}{2}\left(\beta'_{n-1}\Sigma\beta_{n-1} + \sigma^2\right) + \beta'_{n-1} v_{t+1} + e_{n-1}^{t+1} \tag{16}$$

where the first and second components stand for expected return and convexity adjustment while the third and fourth components represent priced return innovation and return pricing error, respectively. When times to maturity and dates are piled into matrices, Eq. (16) turns into:

$$rx = \beta'\left(\lambda_0 \iota'_T + \lambda_1 X_L\right) - \frac{1}{2}\left(B^* \mathrm{vec}(\Sigma) + \sigma^2 \iota_N\right)\iota'_T + \beta' V + E \tag{17}$$

where T denotes the number of trading days in the observation period, N denotes the number of bonds with different times to maturity of which returns are observed every trading day, rx is a $N \times T$ matrix denoting excess holding period returns, β is a $K \times N$ matrix denoting factor loadings, $B^* = \left[\mathrm{vec}\left(\beta_1\beta'_1\right) \ldots \mathrm{vec}\left(\beta_N\beta'_N\right)\right]'$ is a $N \times K^2$ matrix, ι_T and ι_N are $1 \times T$ and $1 \times N$ all-ones matrices, X_L is a $K \times T$ matrix denoting one-period lagged state variables, V is a $K \times T$ matrix denoting VAR residuals, and E is a $N \times T$ matrix denoting return pricing errors.

Adrian et al. (2013) used a three-step regression approach to extract market prices of risk from observed excess holding period returns decomposed as in Eq. (17). First, Eq. (9) is estimated by OLS to break down state variables into a predictable component and an innovation component. An estimator of variance covariance matrix is obtained by the resulting innovation matrix as: $\hat{\Sigma} = \hat{V}\hat{V}/T$. Secondly, excess holding period returns are stated as the linear combination of a constant, innovation matrix, and one-period lagged state variables:

$$rx = \alpha \iota'_T + \beta'\hat{V} + cX_L + E \tag{18}$$

where $\alpha = \beta'\lambda_0 - \frac{1}{2}\left(B^* \mathrm{vec}(\Sigma) + \sigma^2 \iota_N\right)$ and $c = \beta'\lambda_1$ from Eq. (17). Eq. (18) is estimated using OLS, and the resulting mean squared error estimates the variance: $\hat{\sigma}^2 = \mathrm{tr}\left(\hat{E}\hat{E}'\right)/NT$. Then, estimators for market prices of risk are given as:

$$\overline{\lambda_0} = \left(\hat{\beta}\hat{\beta}'\right)^{-1}\hat{\beta}\left(\hat{\alpha} + \frac{1}{2}\left(\hat{B}^* \mathrm{vec}(\hat{\Sigma}) + \hat{\sigma}^2 \iota_N\right)\right) \tag{19}$$

and

$$\hat{\lambda}_1 = \left(\hat{\beta}\hat{\beta}'\right)^{-1}\hat{\beta}\hat{c} \tag{20}$$

Using estimated parameters, log bond prices can be expressed as affine functions of state variables:

$$\ln P_n^t = A_n + B'_n X_t + u_n^t \tag{21}$$

where u_n^t is an error term. Yields are found by annualizing the negative of right-hand side in Eq. (21). A_1 and B_1 are equal to $-\delta_0$ and $-\delta_1$ in Eq. (12) and can be estimated by regressing one-period interest rates on state variables. Using Eqs. (7), (16), and (21), Adrian et al. (2013) showed that long-term yields can be recursively calculated from difference equations:

$$A_n = A_{n-1} + B'_{n-1}\left(\mu - \lambda_0\right) + \frac{1}{2}\left(B'_{n-1}\Sigma B_{n-1} + \sigma^2\right) - \delta_0 \tag{22}$$

and

$$B'_n = B'_{n-1}\left(\phi - \lambda_1\right) - \delta'_1 \tag{23}$$

Yields derived from Eqs. (21), (22), and (23) satisfy no-arbitrage conditions. Convexity-adjusted expected average future short rate component in yields can be found by equating market prices of risk to zero, accordingly, the resulting interest rates denote the risk-neutral yield curve. The remaining component in yields denotes the compensation that investors demand for bearing interest rate risk, thus term premium.

Affine term structure models do not restrain number of state variables to be used for estimating model parameters. State variables also do not have to be yield curve components. For instance, one may select Nelson Siegel parameters directly or macroeconomic variables such as inflation and output growth. We use principal components of daily Nelson Siegel yields which are derived from the eigenvalue decomposition of the covariance matrix of yields as state variables since they are more commonly used than Nelson Siegel parameters. We also standardize state variables before using them as daily pricing factors so that interpretation of model implied factor loadings would be more intuitive. First principal component explains 95.5% of the total variance in yields while corresponding figures are 4.1% and 0.4% for second and third principal components, respectively. We use the first three principal components since they combined explain almost all of the variation in yields.

Following the baseline specification in the ACM model, we take one-month yield as the risk-free rate and calculate excess returns for $n = 6,\ 12, \ldots, 60,\ 84,\ 120$ month discount bonds, making a total of 12 times to maturity. However, we do not use individual bonds since their limited numbers put a limit on available times to maturity. As model parameters are estimated by regressions at monthly frequency, Adrian et al. (2013) suggested aggregating yields either by selecting end of month values or calculating monthly averages. We use monthly averages since the resulting model implied yields fit better to input yields. First, we estimate model parameters using monthly observations. Then, we impute term premia at daily frequency using daily pricing factors.

5. Empirical findings

Firstly, implementation of the ACM model and the resulting term premia estimates are presented. Then, estimated term premia are regressed on a variety of exogenous factors in order to identify their determinants. We focus on term premium in 2-year yield since this time to maturity point is used as a benchmark for the interest rate market. Factors are selected to represent market risk, liquidity risk, credit risk, and behavioral factors.

5.1. Term premia estimation via the ACM model

We estimate the VAR(1) model in Eq. (9) for monthly averages of pricing factors. VAR coefficients, residuals, and variance covariance matrix are obtained from results. Then, we estimate the coefficients in Eq. (18) by regressing one-month excess holding returns calculated from monthly average yield curves as in Eq. (7) on one-month lagged state variables and contemporaneous VAR residuals. Table 2 reports resulting estimates. It is worth pointing out that, compatible with the literature, the sturdiest predictor of future excess holding period returns of long-term bonds is identified as the slope component. In particular, one standard deviation rise in slope component increases expected one-month excess holding return of 10-year bond by 3.8%. Regression intercepts and coefficients of regressors are collected from the results.

Next, we estimate market prices of risk using Eqs. (19) and (20) together with coefficient estimates in the excess return regressions. Before bonds can be priced in ACM model, risk-free rate should be regressed on state variables to estimate coefficients in Eq. (12). Now, with daily pricing factors and all of the model parameters in hand, we use Eqs. (21)–(23) to recursively extract affine model yields for months to maturity 1 to 120. Risk-neutral yields are derived using the same equations by equating all market prices of risk to zero. The difference between physical and risk-neutral yields gives an estimate of term premium. From Eq. (16), annualized n-month yield is estimated as:

$$B'_n = B'_{n-1}\left(\phi - \lambda_1\right) - \delta'_1 \tag{24}$$

Fig. 1 displays that the three-factor affine model satisfactorily fits observed yields and their standard deviations.

Table 2
Excess holding period return regressions.

Regressor	Excess holding period returns (rx_{n-1})					
Panel A. Short terms to maturity						
	6 months	12 months	18 months	24 months	30 months	36 months
Intercept	0.001	0.001	0.001	0.001	0.001	0
V_1	−0.016	−0.037	−0.059	−0.079	−0.098	−0.116
V_2	0.006	0.011	0.014	0.015	0.014	0.011
V_3	0.003	0.002	−0.001	−0.004	−0.007	−0.008
Level (X_1, L)	0.001	0.002	0.002	0.003	0.004	0.004
Slope (X_2, L)	0	0	0	0.001	0.002	0.004
Curvature (X_3, L)	0	0.001	0.002	0.003	0.004	0.004
Observations	194	194	194	194	194	194
Panel B. Long terms to maturity						
	42 months	48 months	54 months	60 months	84 months	120 months
Intercept	0	0	0	−0.001	−0.002	−0.004
V_1	−0.132	−0.147	−0.162	−0.176	−0.226	−0.298
V_2	0.007	0.001	−0.005	−0.012	−0.043	−0.093
V_3	−0.009	−0.009	−0.008	−0.006	0.004	0.022
Level (X_1, L)	0.004	0.005	0.005	0.005	0.006	0.007
Slope (X_2, L)	0.005	0.007	0.009	0.012	0.022	0.038
Curvature (X_3, L)	0.005	0.005	0.005	0.005	0.003	−0.002
Observations	194	194	194	194	134	134

Notes: This table shows coefficient estimates of one-month excess holding period returns on one-month lagged state variables and contemporaneous VAR residuals. Excess holding period returns for times to maturity longer than 5 years are observed between February 2010 and March 2021, however, coefficients stay stable if observation period begins in February 2005 as it does for shorter times to maturity. All coefficients are significant at 0.001 level.

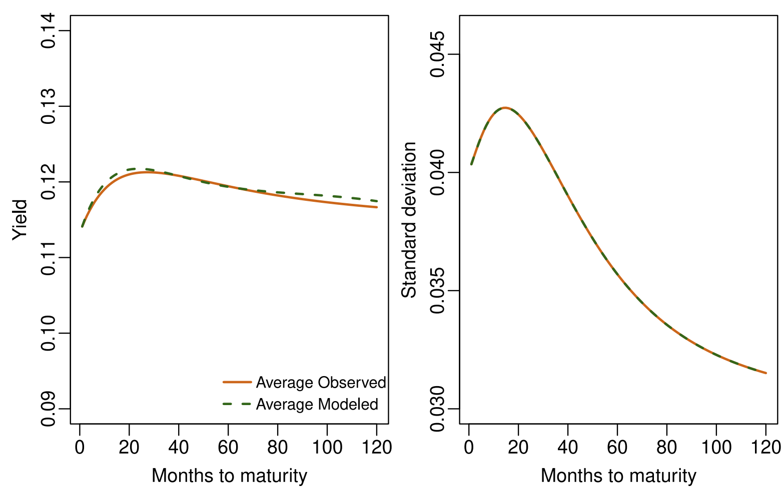

Fig. 1. Means and standard deviations of observed and modeled yields. Notes: This figure displays statistics for observed and modeled yields. Left panel shows mean yields for each term to maturity up to 120 months while right panel shows standard deviations. Solid curves are for Nelson Siegel yields and dashed curves for the yields estimated by three factor affine model.

Consequently, model implied yield loadings for pricing factors can be derived as $-12/nB_n$. Moreover, from the first term in Eq. (16), model implied expected one-month excess return loadings can be calculated as B_n^1. Left panel in Fig. 2 displays model implied yield loadings which could be construed as the response of n-month yield to a standard deviation increase in the respective pricing factor. Loading of the level factor is distinctly higher than loadings of slope and curvature factors and its sign is positive regardless of times to maturity in contrast with those of other factors. Right panel shows that expected excess return loadings that can be considered as the response of expected one-month excess holding return on n-month bond to a standard deviation shock to the respective factor. It seems that slope factor dominates the predictable part of excess returns for long terms to maturity.

Sample statistics for term premia at selected times to maturity are reported in Table 3. It is observed that means of term premium at different times to maturity have a humped shape and peak at approximately 30 months. Standard deviations of term premia, on the other hand, increase with times to maturity of bonds.

We focus on 1, 2, 5, and 10-year yields to evaluate their decomposition into expectation and term premium components. Fig. 3 displays charts of corresponding four time series. Time series of 1-year yield components show that expected average short rates are highly correlated with yields for short-terms. It is observed that term premia in long-term bonds are more volatile and explain a higher fraction of the variation in yields. After the introduction of 10-year bonds in 27 January 2010, 10-year term premia preserved a certain degree of smoothness even during volatile periods in 2018.

2-year term premium peaked in August 2018 when bond market illiquidity measure also peaked. Fig. 4 shows decomposition of yields for the day in which 2-year term premium achieved its maximum value. It seems that the curvature component in yields is abnormally high besides the level component. Since short and long-term yields are not compatible with elevated yields for times to maturity close to 2 years, the ACM model attributes a significant portion of corresponding yields to the risk compensation. This instance suggests that macroeconomic factors such as volatility and ambiguity of foreign exchange parity play major roles as determinants of term premium, seeing that expected future foreign exchange parity is a major component of investors' inflation expectations, and therefore current interest rates.

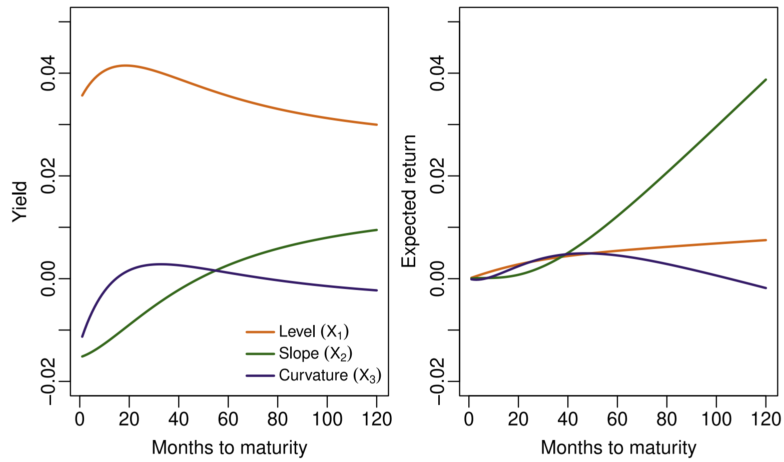

Fig. 2. Model implied yield and expected one-month excess holding return loadings. Notes: This figure displays model implied loadings estimated by the three factor affine model. Left panel shows yield loadings while left panel shows expected one-month excess holding period return loadings.

Table 3
Sample statistics for term premia.

Time to maturity (n)	Statistics for term premia (tp_n)			
	Mean (%)	St. dev. (%)	Minimum (%)	Maximum (%)
6 months	0.41	0.5	−0.54	1.93
12 months	0.72	0.95	−0.92	4.18
18 months	0.88	1.28	−1.26	6.32
24 months	0.95	1.51	−1.55	7.49
30 months	0.97	1.66	−1.78	7.98
36 months	0.96	1.76	−1.96	8.05
42 months	0.94	1.85	−2.1	7.88
48 months	0.92	1.91	−2.22	8.15
54 months	0.91	1.97	−2.31	8.53
60 months	0.9	2.02	−2.86	8.86
84 months	−0.02	1.47	−2.67	6.04
120 months	−0.1	1.53	−2.98	5.74

Notes: This table shows summary statistics for term premia pertaining to observation period of 4085 trading days between 6 January 2005 and 31 March 2021 for times to maturity up to five years and 2812 trading days between 27 January 2010 and 31 March 2021 for longer terms to maturity.

5.2. Determinants of term premium

A major factor determining yields is inflation expectation. However, inflation expectation alone cannot be a determinant of term premium as it is almost always assumed in finance that risk-averse investors demand compensation for the second moment of underlying variables. Thus, a measure of future inflation uncertainty is needed. Aydin and Ozel (2019) proposed using dispersion of responses in inflation expectation surveys, however, surveys are not available on daily basis and their reliability is questionable. Instead, we assume the existence of a credible central bank which aims to keep short-run real interest rates more or less constant. Therefore, implied volatility derived from foreign exchange options reveals a measure of inflation uncertainty, especially when it is provided that the inflation for foreign currency is stabilized. Thus, we use daily observations of one-month implied volatility for USDTRY options. As a robustness check for this measure, we also calculate 21 days rolling window estimate of one-month yield volatility. Furthermore, we use bond market illiquidity measure in Eq. (4) which is the byproduct of yield curve estimation because term premium and illiquidity peak at the same time and seem related.

Although governments are usually assumed to be default-free in their domestic currency debt, credit default swap (CDS) premia on their bonds might rise aloft. We use the CDS premium in domestic currency denominated bonds to test whether credit risk premium is related to term premium. We also use CDS premium in USD denominated Turkish treasury bonds as a robustness check.

Aydin and Ozel (2019) suggested that the percentage of foreign holdings in treasury bonds market be a significant determinant of term premium. Thus, changes in sentiment towards emerging market bonds might be a determinant of term premium. To test this, we use monthly shocks to the Emerging Markets Bonds Sentiment Index (EMBSI) published by Sentix. As a robustness check of this sentiment measure, we use monthly shocks to the Consumer Confidence Index (CCI) published by the Turkish Statistical Institute.

Another possible behavioral determinant of term premium might be ambiguity, though empirical works contributing a measurable factor for it are rarely found on asset pricing in general and interest rate modeling in specific. The nascent but limited literature on the topic relies on macroeconomic ambiguity to document the potential relationship. This study takes a more practical view of financial market ambiguity to empirically test its contribution to term premia. Izhakian (2020) developed the foundation of an ambiguity measure as volatility of probabilities. Brenner and Izhakian (2018) is the first in a line of studies empirically testing the said measure on the stock market. This measure is conceptually simple, intuitive, and applicable for the empirical measurement of the degree of ambiguity across a wide range of markets. To the best of our knowledge, this will be the first study using this novel ambiguity measure in explaining interest rates.

In this study, the methodology developed by Brenner and Izhakian (2018) is employed to measure volatility of probabilities as a consistent measure of ambiguity in currency market, namely USDTRY exchange rate. It is implicitly assumed that the currency ambiguity encompasses all the ambiguity information regarding inflation and other macroeconomic variables and by extension the ambiguity of Turkish bond market and interest rates. As ambiguity is taken to be uncertainty of the probabilities of returns, following Izhakian (2020) ambiguity is defined as:

$$\mho^2[\mathrm{r}] = \int \mathrm{E}[\varphi(\mathrm{r})]\,\mathrm{Var}[\varphi(\mathrm{r})]\mathrm{dr}, \tag{25}$$

where r is the return and $\varphi(r)$ is the marginal probability of returns. While risk can be measured by the volatility of returns, this new measure empirically quantifies ambiguity by the volatility of probabilities.

Following Brenner and Izhakian (2018), 5-minute returns of the exchange rates are retrieved. The website of Forexite provides data for USDTRY which is available between 29 November 2010 and 31 March 2021. The foreign exchange market is open from Australasian market opening on Monday to North American market closing on Friday. This allows us to consider a 5-day week with full 24 h or 288 observations of 5-minute returns each day. For each day, a histogram of returns is derived. Specifically, 5-minute returns are divided into 62 bins, 60 bins for returns between −1% and 1%, and two bins for extreme values

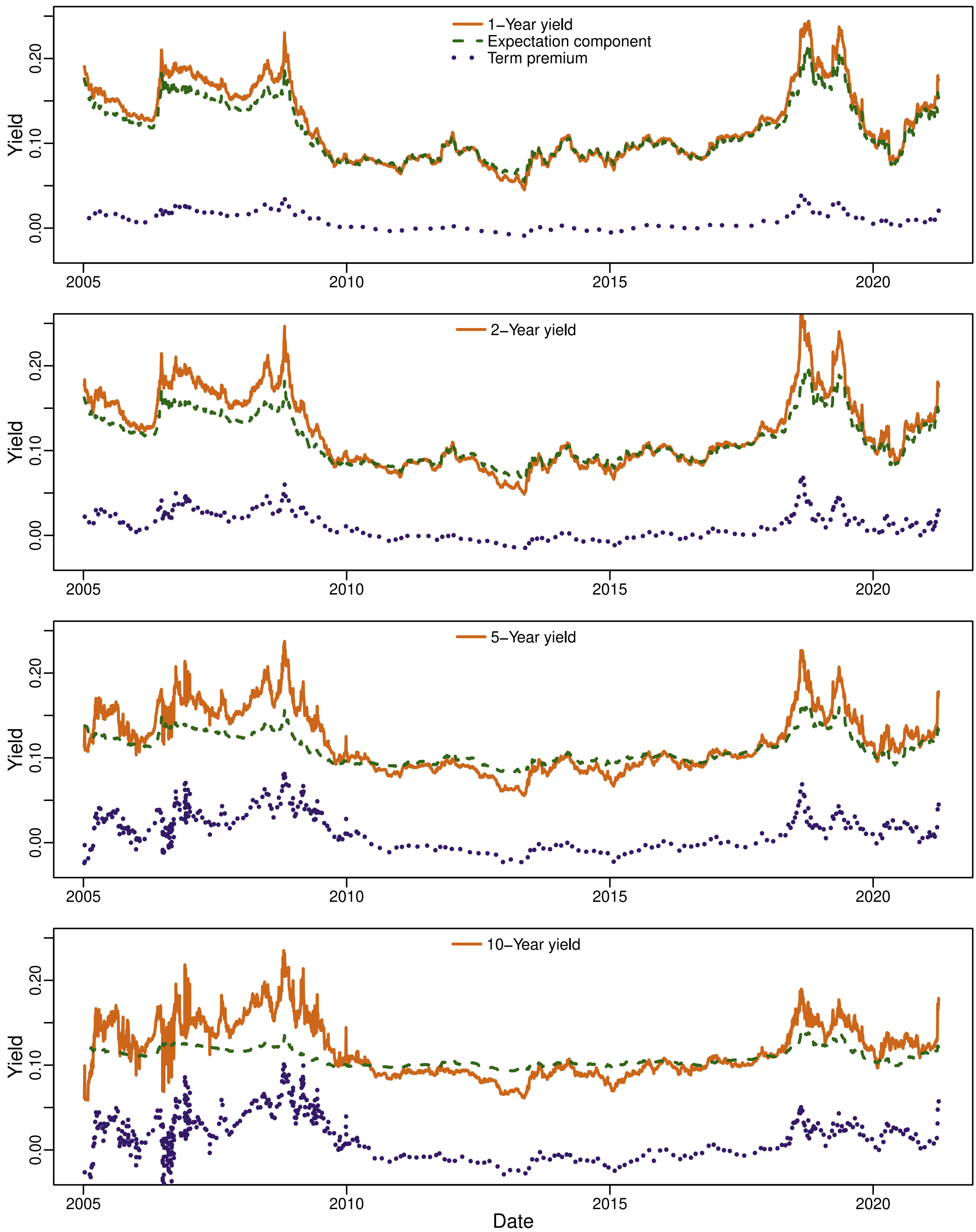

Fig. 3. Time series of term premium and expectation components. Notes: This figure displays time series of yields and their components. From top to bottom, panels show 1-, 2-, 5-, and 10-year yields with their expectation and term premium components.

which are above 1% and below −1%. Second, the probability of returns being in each bin is estimated as the frequency of 5-minute returns within a day. Then, the mean and variance of the probability for each of the 62 bins are calculated. Finally, the degree of foreign exchange ambiguity can be estimated as:

$$\mho^2[r] = \begin{pmatrix} \mathrm{E}\left[\Phi\left(r_0;\mu,\sigma\right)\right]\ \mathrm{Var}\left[\Phi\left(r_0;\mu,\sigma\right)\right] \\ +\sum_{i=1}^{60} \mathrm{E}\left[\Phi\left(r_i;\mu,\sigma\right)-\Phi\left(r_{i-1};\mu,\sigma\right)\right] \\ \times \mathrm{Var}\left[\Phi\left(r_i;\mu,\sigma\right)-\Phi\left(r_{i-1};\mu,\sigma\right)\right] \\ +\mathrm{E}\left[1-\Phi\left(r_{60};\mu,\sigma\right)\right]\ \mathrm{Var}\left[1-\Phi\left(r_{60};\mu,\sigma\right)\right] \end{pmatrix}, \tag{26}$$

where r_0 and r_{60} are the lowest and highest returns ±1% and ϕ denotes the cumulative probability. Interested readers can refer to the original study for the details of the methodology. Our ambiguity measure is computed by a rolling window calculation of Eq. (26) for 30 days with a minimum of 20 days of data at initiation. This rolling window ambiguity measure is then used as an ambiguity estimate for the subsequent day to be incorporated into term premia estimation.

Descriptive statistics for all eight factors are reported in Table 4. Statistics for each factor pertain to different observation periods. Implied volatilities in one-month USDTRY currency options are observed

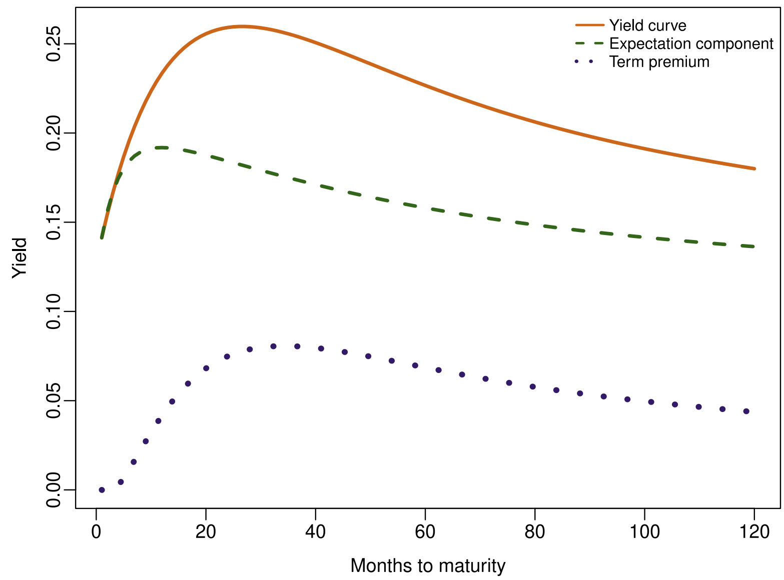

Fig. 4. Decomposition of yield curve as of 17 August 2018. Notes: This figure displays the Turkish treasury yield curve along with its expectation and term premium components as of 17 August 2018.

Table 4
Sample statistics for factors.

Factor	Statistic					
	Mean	St. dev.	Skew.	Kurt.	Min.	Max.
Implied Vol.	15.08	5.6	1.4	2.55	6.38	42.32
Bond yield Vol.	0.004	0.003	2.43	9.41	0.001	0.028
Illiquidity	0.001	0.001	4.42	26.78	0	0.014
2-Year CDS (TL)	149.9	92.3	1.02	0.09	35.6	439
2-Year CDS (USD)	187.1	122.1	1.56	1.99	49.7	834.9
Shocks to EMBSI	0.03	5.88	−1.15	3.55	−24.5	13.25
Shocks to CCI	−0.04	2.37	0.06	1.12	−7.04	8.93
Ambiguity	0.008	0.004	1.51	3.47	0.001	0.03

Notes: This table shows summary statistics of factors that are selected to test whether they explain variation in term premia.

Table 5
Univariate term premium regressions.

Regressor	2-Year term premium			
	Coefficient	Constant	N	R^2
Implied volatility	2.09***	−0.02***	1141	0.7
	−32.69	(−23.28)		
CDS premium	8.64***	−0.00***	1485	0.38
	−19.65	(−5.88)		
Bond market illiquidity	7.15***	0	4085	0.36
	−24.89	(−0.59)		
EM bonds sentiment shock	−1.45***	0.01***	3502	0.01
	(−3.11)	−29.47		
Ambiguity	−7.46***	0.01***	2588	0.06
	(−16.33)	−19.36		

Notes: This table shows coefficient estimates for univariate regressions of 2-year term premium on various factors measured daily. Factors were scaled with powers of 10 in order to ensure that they have the same order of magnitude. Robust *t*-statistics are shown in parentheses.
***Indicates a significance level of 0.001.

between 3 February 2016 and 21 August 2020. Since we used 21-day rolling window to estimate one-month bond yield volatility, the factor is observed between 8 February 2005 and 31 March 2021. Bond market illiquidity is available for each trading day between 6 January 2005 and 31 March 2021. CDS premia for treasury bonds denominated in domestic currency and foreign currency are observed until 31 March 2021 starting from 7 May 2015 and 8 August 2008, respectively. EMBSI and CCI are updated once per month according to survey responses. Therefore, values of the monthly shocks to these indices stay the same during each month. These factors are observed until 31 March 2021 starting from 30 April 2007 and 31 January 2007, respectively. Ambiguity is observed between 21 December 2010 and 31 March 2021. All observed values are used in univariate regressions on factors while the longest observation period which is common in all factors are used in multivariate regressions. Fig. 5 displays time series of factors.

First, 2-year term premium is regressed on factors one by one. Table 5 reports the resulting coefficient estimates all of which turn out to be significant at 0.001 level. Implied volatility derived from currency options explains 70% of the variation in 2-year term premium. As expected, it has a positive coefficient since uncertainty in macroeconomic factors, especially inflation, should increase compensation for risk that investors demand. CDS premium for TL denominated bonds explains the second highest variance in 2-year term premium. Its positive coefficient shows that a significant portion of sources of credit risk is common in interest rate risk. Bond market illiquidity explains a similar portion of the variance in term premium. It also has a positive slope indicating that exposure to the noise in bond prices affects interest rate risk component in yields.

Monthly shocks to the Emerging Markets Bonds Sentiment Index (EMBSI) factor has a negative coefficient that is typical for sentiment measures. On the other hand, the factor explains as low as 1% of the variation in term premia, which is expected since surveys respond to the market developments after a time lag. Lastly, an increase in ambiguity predicts decreasing 2-year term premium. During times of elevated ambiguity in the economy, ambiguity-averse investors would expect worst-case scenario and forego higher return in exchange for less risk. Although treasury bonds lose a portion of their value in large scale market downturns, a sovereign default is an unlikely event. Therefore, compared to other financial instruments such as equities, treasury bonds are generally considered a safe haven investment. For this reason, the negative sign of ambiguity coefficient might stem from flight-to-safety to treasury bonds from other assets. Nevertheless, the assumption of ambiguity aversion requires further justification to devise reliable explanations for the interaction between ambiguity and other variables.

Coefficient estimates in multivariate regressions require a robustness control when factors are suspected of multicollinearity. We calculate variance inflation factors (VIF) for each coefficient and report them

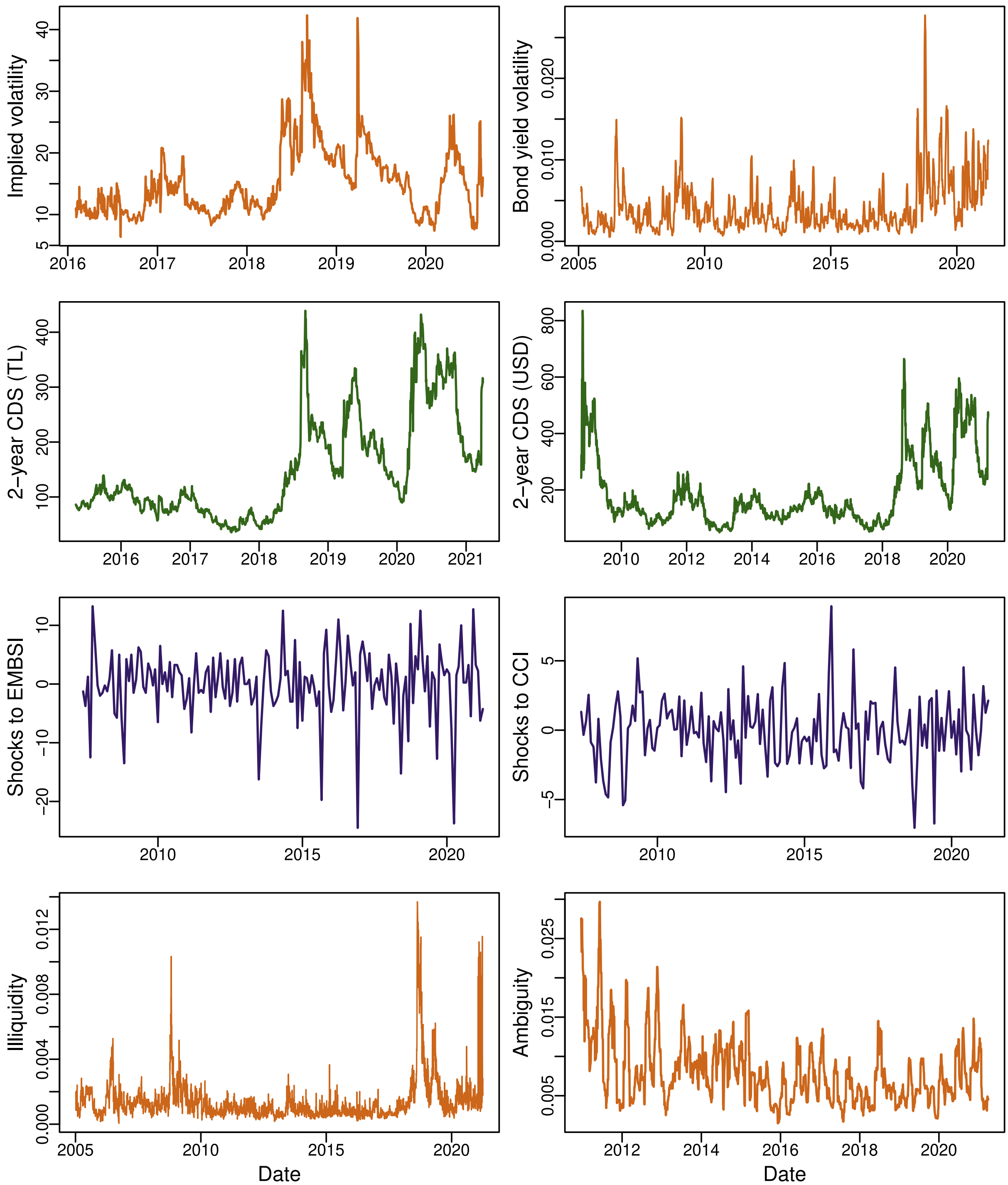

Fig. 5. Time series of factors as determinants of term premia. Notes: This figure displays the time series of financial variables of interest.

in brackets. A coefficient estimate with a VIF measure higher than 5 is considered unreliable. We regress 2-year term premium on the five factors at the same time. Table 6 reports the results. It is seen that VIF measures do not indicate a severe multicollinearity problem. Thus, we proceed with interpreting coefficients and their significance levels. The first regression shows that factors in Table 5 combined explain 81% of the variation in 2-year term premium. All of the coefficients are still significant at 0.01 level. Signs of all coefficients are identical to those in univariate regressions. Thus, explanations made there are supported by multivariate regression.

The majority of the explanation power stems from option implied volatility. Therefore, second regression substitutes it with bond yield volatility measure to see how other factors perform. Bond yield volatility has a positive coefficient that is significant at 0.01 level while proportion of the variance explained drops to 70%. Another change is that the significance of ambiguity measure drops to 0.05 level. Since implied volatility includes inflation uncertainty information which is unspanned by other factors, discarding it diminishes the need for adjusting it according to investors' sentiments. Third regression substitutes CDS premium on USD denominated bonds with that on TL denominated bonds. Fraction of the explained variance increases a bit while coefficients of other factors stay the same. Increases in both the explanation power of regression and the significance of related regressor coefficient suggest that CDS premium for debt in foreign

Table 6
Multivariate 2-Year term premium regressions.

Regressor	2-Year term premium			
	(1)	(2)	(3)	(4)
Market Risk Measures				
Option implied	1.11***		1.09***	1.10***
Volatility	−16.45		−16.42	−16.8
	[2.85]		[2.85]	[2.85]
Bond yield		0.36***		
Volatility		−4.47		
		[1.78]		
Liquidity Risk Measure				
Bond market	3.13***	4.45***	3.04***	2.94***
Illiquidity	−14.04	−15.08	−13.84	−13.29
	[2.65]	[1.63]	[2.70]	[2.76]
Credit Risk Measures				
2-Year CDS premium	1.87***	3.45***		1.90***
TL Denominated	−5.97	−10.13		−6.16
	[1.75]	[1.62]		[1.75]
2-Year CDS premium			1.51***	
USD Denominated			−7.07	
			[1.85]	
Behavioral Factors				
EM bonds sentiment	−1.78***	−1.39***	−1.78***	
Shock	(−6.42)	(−5.55)	(−6.4)	
	[1.00]	[1.01]	[1.00]	
Consumer confidence				−4.16***
Shock				(−4.33)
				[1.13]
Ambiguity	−3.36***	−2.27**	−3.42***	−3.18***
	(−4.23)	(−2.48)	(−4.33)	(−3.92)
	[1.05]	[1.08]	[1.05]	[1.06]
Constant	−0.01***	−0.00***	−0.01***	−0.01***
	(−13.76)	(−5.58)	(−13.91)	(−13.45)
Observations	1141	1485	1141	1141
R^2	0.81	0.7	0.82	0.81

Notes: This table shows coefficient estimates for four term premium regressions on different combinations of factors which are measured daily. Factors were scaled with powers of 10 in order to ensure that they have the same order of magnitude. Robust *t*-statistics are shown in parentheses. Variance Inflation Factors are shown in brackets.
**Indicate significance levels of 0.05.
***Indicate significance levels of 0.01.

Table 7
Multivariate term premia regressions.

Regressor	Term premium		
	1-year	5-year	10-year
Market Risk Measure			
Option implied	0.76***	0.98***	0.59***
Volatility	−17.64	−14.27	−8.66
	[2.91]	[2.81]	[2.93]
Liquidity Risk Measure			
Bond market	2.07***	2.25***	1.37***
Illiquidity	−13.31	−10.89	−6.54
	[2.74]	[2.58]	[2.52]
Credit Risk Measures			
1-Year CDS premia	0.39		
TL Denominated	−1.5		
	[2.02]		
5-Year CDS premia		4.68***	
USD Denominated		−21.19	
		[1.53]	
10-Year CDS Premia			8.45***
USD Denominated			−24.39
			[1.51]
Behavioral Factors			
EM bonds sentiment	−0.71***	−1.71***	−0.46
Shock	(−3.77)	(−5.56)	(−1.34)
	[1.00]	[1.00]	[1.01]
Ambiguity	−3.32***	−0.98	0.64
	(−6.13)	(−1.08)	−0.63
	[1.05]	[1.06]	[1.06]
Constant	−0.00***	−0.02***	−0.03***
	(−8.62)	(−24.12)	(−27.21)
Observations	1141	1141	1141
R^2	0.78	0.79	0.69

Notes: This table shows coefficient estimates for 1-year, 5-year, and 10-year term premia regressions on various factors measured daily. Factors were scaled with powers of 10 in order to ensure that they have the same order of magnitude. Robust *t*-statistics are shown in parentheses. Variance Inflation Factors are shown in brackets.
***Indicates a significance level of 0.01.

currency include information that is unspanned by that in domestic currency. Fourth regression substitutes monthly shocks to the consumer confidence with monthly shocks to the EM bonds sentiment. Coefficient of the monthly shocks to the CCI is negative and significant at 0.01 level, as well. Therefore, it can be concluded that two sentiment factors carry similar information regarding 2-year term premium. We run regressions to test how factors determine term premia for shorter and longer times to maturity. Table 7 reports the results. VIF measures indicate that there is no severe multicollinearity problem for regressions of 1, 5, and 10-year term premia. Hence, we move to interpreting the coefficients and their significance levels.

First regression shows that CDS premium does not significantly contribute to 1-year term premium while other factors are significant determinants of it at 0.001 level. It is observed that both significance level and coefficient of CDS premia as a determinant of term premia increase with the horizon. This contrasts with volatility measures which lose some part of their significance as determinants of term premia with increasing horizon. On the other hand, sentiment-related measures lose their significance completely as determinants of term premia for the endmost time to maturity. Shocks to the EM bonds sentiment factor are insignificant for 10-year term premium while ambiguity does not significantly contribute to 5 and 10-year term premia. All in all, five factors combined explain 78% and 79% of the variations in 1 and 5-year term premia, respectively. Since impacts of market risk, liquidity, and behavioral measures on term premia decline at the long end of maturity horizon, only 69% of the variation in 10-year term premium can be explained. Moreover, negative sign of the intercept for 10-year term premium indicates that another factor might be a determinant of term premium for the longest terms to maturity.

6. Conclusion

In this study, we decomposed Turkish treasury yield curve into expectation and interest risk premium components. We derived the yield data directly from price quotes in the bond market. For every trading day in the observation period, we fitted Nelson–Siegel curves to obtain continuous functions which reasonably estimate yields for times to maturity that are unspanned by traded bonds. Resulting yield curves are used as input to construct a three-factor ACM affine term structure model. Model parameters are estimated by linear regressions, and results are used with daily pricing factors to obtain estimates of risk-neutral yields. Term premia for each maturity are estimated by subtracting risk-neutral yields from estimated nominal yields.

Literature on the topic investigates possible determinants of term premium in treasury yields. We conjecture that financial markets offer more timely and forward-looking information over the possible macroeconomic indicators. Hence most of our factors are extracted from financial data. To contribute in this aspect, we select four groups of factors to test whether they determine term premia. In order to incorporate market risk, we use the option implied volatility of USDTRY exchange rate. We alternatively use realized bond yield volatility as a robustness test. We use the CDS premia for domestic and foreign currency denominated bonds as credit risk measures. We form a bond market illiquidity measure from the discrepancies in bond prices in order to test if there is a liquidity premium in bond yields. Lastly, we use a novel ambiguity measure derived from foreign exchange market in order o gauge the impact of ambiguity aversion, with additional behavioral aspects captured by the shocks to market sentiment and consumer confidence indices.

Putting the emphasis on term premium in benchmark 2-year yield, we regress term premia at different horizons on factors. Results indicate that all these factors significantly contribute to term premia and can explain more than 80% of its variation, with the major explanation power pertaining to the implied volatility in currency options. It should be noted that our explanatory power is considerably higher than studies with different set of variables. Contribution of market risk on term premia displays a hump-shaped effect rising up-to 5-year horizons and diminishing in longer horizons. The impact of credit risk measures increases with the maturity horizon as expected as the longer the holding period, the higher the risk of default for any fixed income security. Surprisingly, the effect of illiquidity diminishes with maturity horizon. Extant literature argues that bonds with longer maturities are less liquid, hence they have to offer an illiquidity premium to entice potential investors. Our results show that although there is a positive illiquidity premium within the term premia for all maturities, the coefficient slightly goes down for the longest end of the yield curve. Among the behavioral factors, effect of sentiment measures in determining term premia in the longest-term bonds cease to exist, although it shows a negative impact on term premia of shorter maturities.

In the most notable contribution of the study, our results show that ambiguity is a priced factor in term premia. More importantly, rising ambiguity reduces the term premia in the shorter end of the yield curve implying a strong flight-to-safety behavior by ambiguity-averse investors. As short-term government bonds are considered safe assets in times of higher ambiguity, this behavior is expected. The coefficient for the longest maturity becomes positive, albeit statistically insignificant, implying ambiguity premium demanded by investors. Our results are in line with findings of Leippold and Matthys (2022), as they show a similar pattern in response of bond risk premia in the US to EPU. Their test with term premia, however, do not display a significant pattern. We also would like to note that explanatory power of our regression model is significantly higher than theirs. The implication of our findings is that ambiguity and ambiguity-averse behavior of investors partly explain the shape of the upward-sloping yield curve. Furthermore, the central banks should aim to lessen ambiguity in the exchange rates, and by extension the entire financial markets, through more transparent monetary policy along with their stated policy of reducing volatility in exchange rates.

CRediT authorship contribution statement

Cenk C. Karahan: Conceptualization, Methodology, Data curation, Formal analysis, Writing – review & editing, Supervision. **Emre Soykök:** Methodology, Formal analysis, Visualization, Writing – original draft.

References

Adrian, T., Crump, R. K., & Moench, E. (2013). Pricing the term structure with linear regressions. *Journal of Financial Economics*, *110*(1), 110–138. http://dx.doi.org/10.1016/j.jfineco.2013.04.009.

Akgiray, V., Baronyan, S., Sener, E., & Yılmaz, O. (2016). Predictability of emerging market local currency bond risk premia. *Emerging Markets Finance and Trade*, *52*(7), 1627–1646. http://dx.doi.org/10.1080/1540496X.2015.1011555.

Ang, A., & Piazzesi, M. (2003). A no-arbitrage vector autoregression of term structure dynamics with macroeconomic and latent variables. *Journal of Monetary Economics*, *50*(4), 745–787. http://dx.doi.org/10.3386/w8363.

Aydin, H. I., & Ozel, O. (2019). *Term premium in turkish lira interest rates (working paper no. 19/33)*. Central Bank of the Republic of Turkey, Retrieved from https://www.tcmb.gov.tr/.

Baker, S., Bloom, N., & Davis, S. J. (2016). Measuring economic policy uncertainty. *Quarterly Journal of Economics*, *131*, 1593–1636. http://dx.doi.org/10.1093/qje/qjw024.

Bauer, M. D., & Rudebusch, G. D. (2020). Interest rates under falling stars. *American Economic Review*, *110*(5), 1316–1354. http://dx.doi.org/10.1257/aer.20171822.

Breach, T., D'Amico, S., & Orphanides, A. (2020). The term structure and inflation uncertainty. *Journal of Financial Economics*, *138*(2), 388–414. http://dx.doi.org/10.1016/j.jfineco.2020.04.013.

Brenner, M., & Izhakian, Y. (2018). Asset pricing and ambiguity: empirical evidence. *Journal of Financial Economics*, *130*(3), 503–531. http://dx.doi.org/10.1016/j.jfineco.2018.07.007.

Bretscher, L., Hsu, A., & Tamoni, A. (2020). Fiscal policy driven bond risk premia. *Journal of Financial Economics*, *138*(1), 53–73. http://dx.doi.org/10.1016/j.jfineco.2020.04.010.

Campbell, J. Y., & Shiller, R. J. (1991). Yield spreads and interest rate movements: a bird's eye view. *Review of Economic Studies*, *58*(3), 495–514. http://dx.doi.org/10.2307/2298008.

Cepni, O., & Güney, I. E. (2019). Local currency bond risk premia: A panel evidence on emerging markets. *Emerging Markets Review*, *38*, 182–196. http://dx.doi.org/10.1016/j.ememar.2019.01.002.

Cochrane, J. H., & Piazzesi, M. (2005). Bond risk premia. *American Economic Review*, *95*(1), 138–160. http://dx.doi.org/10.1257/0002828053828581.

Cochrane, J. H., & Piazzesi, M. (2009). Decomposing the yield curve. *SSRN Electronic Journal*, http://dx.doi.org/10.2139/ssrn.1333274.

Dai, Q., & Singleton, K. J. (2002). Expectation puzzles, time-varying risk premia, and affine models of the term structure. *Journal of Financial Economics*, *63*(3), 415–441. http://dx.doi.org/10.1016/S0304-405X(02)00067-3.

De Graeve, F., Emiris, M., & Wouters, R. (2009). A structural decomposition of the us yield curve. *Journal of Monetary Economics*, *56*(4), 545–559. http://dx.doi.org/10.1016/j.jmoneco.2009.03.013.

Diebold, F. X., & Li, C. (2006). Forecasting the term structure of government bond yields. *Journal of Econometrics*, *130*(2), 337–364. http://dx.doi.org/10.1016/j.jeconom.2005.03.005.

Duffee, G. R. (2002). Term premia and interest rate forecasts in affine models. *The Journal of Finance*, *57*(1), 405–443. http://dx.doi.org/10.1111/1540-6261.00426.

Duffee, G. R. (2018). Expected inflation and other determinants of treasury yields. *The Journal of Finance*, *73*(5), 2139–2180. http://dx.doi.org/10.1111/jofi.12700.

Fama, E. F. (1984). Term premiums in bond returns. *Journal of Financial Economics*, *13*(4), 529–546. http://dx.doi.org/10.1016/0304-405X(84)90014-X.

Fama, E., & Bliss, R. (1987). The information in long-maturity forward rates. *The American Economic Review*, *77*(4), 680–692. http://dx.doi.org/10.7208/9780226426983-025.

Gagliardini, P., Porchia, P., & Trojani, F. (2009). Ambiguity aversion and the term structure of interest rates. *Review of Financial Studies*, *22*(10), 4157–4188. http://dx.doi.org/10.1093/rfs/hhn092.

Giacoletti, M., Laursen, K. T., & Singleton, K. J. (2021). Learning from disagreement in the US treasury bond market. *The Journal of Finance*, *76*(1), 395–441. http://dx.doi.org/10.1111/jofi.12971.

Gilles, C. (1996). Volatility and the treasury yield curve (paper no. 1). In *Bank for international settlements conference papers* (pp. 228–242). Retrieved from https://www.bis.org/.

Guidolin, M., & Rinaldi, F. (2013). Ambiguity in asset pricing and portfolio choice: a review of the literature. *Theory and Decision*, *74*(2), 183–217. http://dx.doi.org/10.1007/s11238-012-9343-2.

Gurkaynak, R., Sack, B., & Wright, J. (2007). The U.S. treasury yield curve: 1961 to the present. *Journal of Monetary Economics*, *54*(8), 2291–2304. http://dx.doi.org/10.1016/j.jmoneco.2007.06.029.

Gurkaynak, R., & Wright, J. H. (2012). Macroeconomics and the term structure. *Journal of Economic Literature*, *50*(2), 331–367. http://dx.doi.org/10.1257/jel.50.2.331.

Hardouvelis, G. A. (1994). The term structure spread and future changes in long and short rates in the g7 countries: is there a puzzle? *Journal of Monetary Economics*, *33*(2), 255–283. http://dx.doi.org/10.1016/0304-3932(94)90003-5.

Hofmann, B., Shim, I., & Shin, H. S. (2020). Bond risk premia and the exchange rate. *Journal of Money, Credit and Banking*, *52*(2), 497–520. http://dx.doi.org/10.1111/jmcb.12760.

Hu, G. X., Pan, J., & Wang, J. (2013). Noise as information for illiquidity. *The Journal of Finance*, *68*(6), 2341–2382. http://dx.doi.org/10.1111/jofi.12083.

Izhakian, Y. (2020). A theoretical foundation of ambiguity measurement. *Journal of Economic Theory*, *187*, Article 105001. http://dx.doi.org/10.1016/j.jet.2020.105001.

Joslin, S., & Le, A. (2021). Interest rate volatility and no-arbitrage affine term structure models. *Management Science*, *67*(6), 3321–3341. http://dx.doi.org/10.1287/mnsc.2020.3858.

Joslin, S., Priebsch, M., & Singleton, K. J. (2014). Risk premiums in dynamic term structure models with unspanned macro risks. *The Journal of Finance*, *69*(3), 1197–1233. http://dx.doi.org/10.1111/jofi.12131.

Joslin, S., Singleton, K. J., & Zhu, H. (2011). A new perspective on Gaussian dynamic term structure models. *Review of Financial Studies*, *24*(3), 926–970. http://dx.doi.org/10.2139/ssrn.1364889.

Karahan, C. C., & Soykok, E. (2022). *Term structure of interest rates, noise and liquidity spillover for an emerging market*. Manuscript submitted for publication.

Kim, D. H., & Orphanides, A. (2007). The bond market term premium: what is it, and how can we measure it? *BIS Quarterly Review*, *2007*, Retrieved from https://www.bis.org/.

Kim, D. H., & Orphanides, A. (2012). Term structure estimation with survey data on interest rate forecasts. *Journal of Financial and Quantitative Analysis*, *47*(1), 241–272. http://dx.doi.org/10.1017/S0022109011000627.

Knight, F. H. (1921). *Risk, uncertainty, and profit*. Boston: Houghton Mifflin.

Leippold, M., & Matthys, F. (2022). Economic policy uncertainty and the yield curve. *Review of Finance*, *26*(4), 751–797. http://dx.doi.org/10.1093/rof/rfac031.

Li, C., Meldrum, A., & Rodriguez, M. (2017). Robustness of long-maturity term premium estimates. In *Finance and Economics Discussion Series, Board of Governors of the Federal Reserve System (working paper no. 2017-04-03)*. http://dx.doi.org/10.17016/2380-7172.1927.

Mallick, S., Mohanty, M. S., & Zampolli, F. (2017). *Market volatility, monetary policy and the term premium (working paper no. 606)*. Bank for International Settlements, Retrieved from https://ssrn.com/.

Nelson, C., & Siegel, A. (1987). Parsimonious modeling of yield curves. *Journal of Business*, *60*(4), 473–489. http://dx.doi.org/10.3386/w1594.

Nguyen, T. (2021). Public debt, consumption growth, and the slope of the term structure. In *The review of financial studies*. Advance online publication., http://dx.doi.org/10.1093/rfs/hhab123.

Ozbek, I., & Talaslı, I. (2020). Term premium in emerging market sovereign yields: role of common and country specific factors. *Central Bank Review*, *20*(4), 169–182. http://dx.doi.org/10.1016/j.cbrev.2020.09.003.

Solis, P. (2021). *Term premia and credit risk in emerging markets: The role of u.s. monetary policy (unpublished manuscript)*. Baltimore, MD: John Hopkins University, http://dx.doi.org/10.2139/ssrn.3973655.

Ulrich, M. (2013). Inflation ambiguity and the term structure of US government bonds. *Journal of Monetary Economics*, *60*(2), 295–309. http://dx.doi.org/10.1016/j.jmoneco.2012.10.015.

Wood, J. H. (1964). The expectations hypothesis, the yield curve, and monetary policy. *Quarterly Journal of Economics*, *78*(3), 457–470. http://dx.doi.org/10.2307/1879477.

Wright, J. H. (2011). Term premia and inflation uncertainty: empirical evidence from an international panel dataset. *The American Economic Review*, *101*(4), 1514–1534. http://dx.doi.org/10.1257/aer.101.4.1514.

Zhao, G. (2020). Ambiguity, nominal bond yields, and real bond yields. *American Economic Review: Insights*, *2*(2), 177–192. http://dx.doi.org/10.1257/aeri.20190155.