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Interest rate uncertainty and the shape of the yield curve of U.S. treasury bonds

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Abstract
We decompose the yield curve of U.S. Treasury bonds into three components—the level, slope, and curvature. We then explore the interaction between these factors and uncertainty in the U.S. bond market. We assess this uncertainty using a VIX-style estimate originating in options on the CBOE's Treasury Note futures. Using monthly data for 2003–2020, we find that interest rate uncertainty drives the evolution in the shape of the yield curve, but not vice versa. Specifically, the bond market's VIX-style metric not only correlates with but also influences the yield curve's level and slope. Moreover, increased uncertainty about interest rates is negatively associated with, and can significantly influence, the yield curve's curvature. The results of this study are crucial for both policymakers and money managers.

Keywords Interest rate uncertainty · Monetary surprises · Monetary shocks · Uncertainty · Term structure

JEL Classification C53 · E43 · E47

1 Introduction

The U.S. Treasury market is one of most important markets in the world. Institutions such as money market funds and banks worldwide always refer to the U.S. Treasury market as a bedrock of the global banking system (e.g., He et al., 2019). In addition, the empirical finance literature has established that bond yields in the U.S. have substantial explanatory power for future economic growth. Hence, central bankers and economists always regard interest rates on U.S. Treasuries as a promising indicator of where the economy is heading (e.g., Argyropoulos & Tzavalis, 2016; McMillan, 2021).

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Fig. 1 Uncertainty about interest rates (TYVIX) and latent factors over time. *Notes*: **a** The TYVIX and the Level of the Yield Curve of U.S. Treasury Bonds. **b** The TYVIX and the Slope of the Yield Curve of U.S. Treasury Bonds. **c** The TYVIX and the Curvature of the Yield Curve of U.S. Treasury Bonds. The figures depict the level, slope and curvature of the bond yields (plotted in blue and scaled using the right-hand vertical axis) with the TYVIX (plotted in red and scaled using the left-hand vertical axis) for January 2003 to April 2020. The correlation between interest rate uncertainty and the three factors of the yield curve is 0.45, 0.58, and −0.44, respectively. The level, slope and curvature factors are computed using the procedure suggested by Nelson and Siegel (1987) and Diebold et al. (2006)

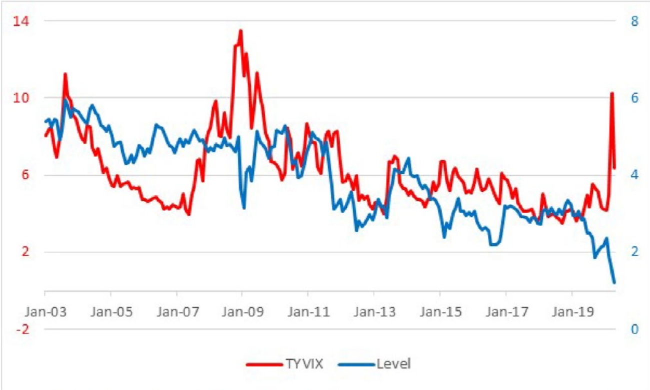
Policymakers make their decisions regarding monetary policy on limited information and in an environment of uncertainty about the economy. Nevertheless, the implementation of the policy itself can also induce uncertainty on its own. Interest rate uncertainty, therefore, refers to the ambiguity surrounding the future trajectory of interest rates within an economy. In this spirit, recent literature examines how surprises in monetary policy, announcements from central banks and the tone of their language affect market participants' expectations regarding nominal and real short- and long-term interest rates (e.g., Bauer et al., 2022; De Pooter et al., 2021; Kaminska et al., 2021).

Despite these efforts, the literature is largely silent regarding the links between uncertainty about interest rates and the entire shape of the yield curve including its level, slope and curvature. The literature has established that the shape of the yield curve is informative and serves as an early warning indicator of the deterioration or improvement in macroeconomic variables (e.g., Seip & Zhang, 2021; Yang, 2020), equity prices (e.g., Faria & Verona, 2020; McCown, 2001) and commodities (Idilbi-Bayaa & Qadan, 2022). Moreover, the shape of the term structure itself can be a policy target, considering its direct effects on the real economy.

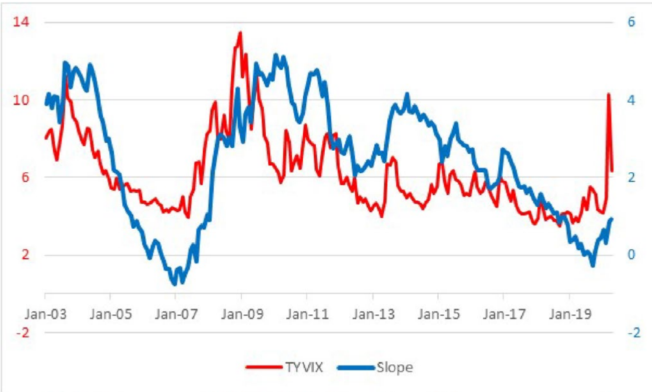
Given these insights, the aim of this paper is to fill this gap and explore the interplay between uncertainty about interest rates and the factors shaping the yield curve: its level, slope and curvature. To do so, we utilize the CBOE's 10-Year Treasury Note Volatility Futures Index (TYVIX) to capture uncertainty in the U.S. bond market. This index is a VIX-style measure that reflects the implied volatility of 10-year Treasury futures. It is computed utilizing the same procedure used in calculating the well-known VIX of the S&P 500 index and put and call options on 10-year U.S. Treasury futures. We also follow the procedure suggested by Diebold and Li (2006), which is based on Nelson and Siegel's (1987) framework. Thus, we measure the three latent factors of the U.S. term structure—the level, slope and curvature—using a diverse set of yield maturities of the U.S. sovereign bond curve from January 2003 to April 2020. We then conduct a Granger (1980) causality test to investigate the possibility of any feedback effects between the elements of the yield curve, and vice versa. Finally, we expand our investigation and use the impulse response analysis to demonstrate how shocks to the uncertainty about interest rates affect each latent factor.

Our findings show that shocks to interest rate uncertainty drive the evolution in the shape of the yield curve, but not vice versa. We establish that the VIX-style measure of uncertainty about bonds correlates with and can affect the future evolution of both the level of interest rates and the slope of the yield curve. Our results

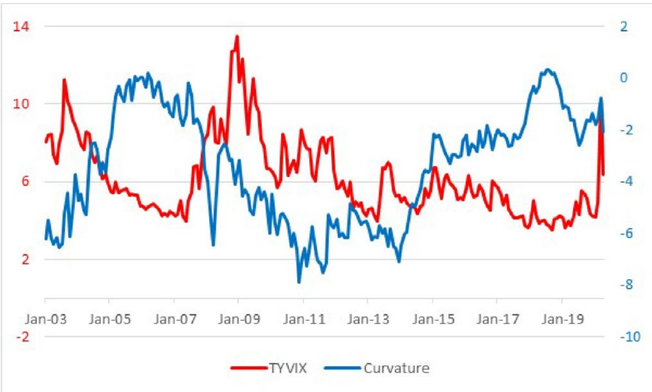
(a) The TYVIX and the Level of the Yield Curve of U.S. Treasury Bonds



(b) The TYVIX and the Slope of the Yield Curve of U.S. Treasury Bonds



(c) The TYVIX and the Curvature of the Yield Curve of U.S. Treasury Bonds



indicate that a decline in interest rate uncertainty is followed by a moderation (or decline) in the slope of the curve, meaning the 10-year minus 3-month rates. In addition, increased uncertainty is followed by a rise in the slope of the yield curve, originating in the decline in short-term interest rates. Figure 1a, b illustrate these relationships. In addition, the results of the Granger-causality test detailed in the empirical findings section confirm our statistical inferences. Lastly, we demonstrate that heightened uncertainty about interest rates negatively correlates with and can shape the curvature of the yield curve. Figure 1c shows that more uncertainty about interest rates is associated with a low degree of curvature. In addition, less uncertainty about interest rates is associated with a high curvature in the yield curve.

Our results are robust to other proxies for uncertainty about interest rates over time. We follow the CBOE's White Paper methodology and compute the "model-free" variance (i.e., the VIX) of 20 + Year Treasury Bonds. Specifically, we use information revealed in the options written on the 20 + Year Treasury Bond ETF (VIX_{20}). This ETF tracks the investment performance of an index comprised of U.S. Treasury bonds with maturities exceeding 20 years. The results obtained are qualitatively similar and remain consistent.

Our results accord with recent works attempting to explain the movements of the yield curve. For example, Stillwagon (2015) rejected the expectation hypothesis, which is commonly invoked to predict longer-term interest rates. This rejection was not limited to the T-bill market but also extended to the Libor markets in the US, UK, and Switzerland. Additionally, the author found evidence supporting the existence of time-varying risk premiums. He also noted that the term premium appears to move inversely with consumer sentiment. This result implies that heightened economic pessimism leads to a stronger preference for shorter-term assets and, consequently, an increase in the premium for longer-term assets. In a later study Stillwagon (2018) reported that the difference between conventional Treasury rates and rates on Treasury Inflation Protected Securities (TIPS) correlates negatively with the level of panic measured by the VIX.

Our findings can be interpreted within the New Keynesian framework where increased uncertainty about interest rates acts as a negative demand shock that reduces inflation and short-term interest rates. Recent theoretical and empirical frameworks confirm this perception. They maintain that the uncertainty surrounding interest rates serves as a critical macroeconomic indicator, affecting both the growth and variability of real economic activity (e.g., Cremers et al., 2021; Mumtaz & Zanetti, 2013; Sinha, 2016).

This study makes at least two main contributions to the literature. First, we introduce a new measure of uncertainty constructed using put and call options on 10-year U.S. Treasury futures. This is a VIX-style measure and has at least four advantages. First, it is a market-based measure of conditional volatility of the 10-year Treasury rate and is a forward-looking measure of volatility. Second, it is not based on a specific option-pricing model such as the Black and Scholes model. Therefore, it is a model-free implied volatility index. Third, it reflects the market's estimate of variance independent of the market level, because it extracts information from options on U.S. Treasury futures across wide range of strike prices instead of a single option, as in the case of Black and Scholes' implied volatility. Accordingly, aggregating information across options should be informationally more efficient than Black and Scholes' implied volatility. Early on, Jiang and Tian (2005) established that model-free implied volatility subsumes all information implicit in both the Black and Scholes' implied volatility index and past-realized volatility. Thus, using this procedure with Treasury derivatives can produce a more efficient forecast of the future realized volatility of interest rates. Fourth, this forward-looking volatility measure is derived from the put and call prices of highly liquid derivative instruments, and data about them are available daily.

Given these important advantages, the suggested measure allows us to explore how changes in the forward-looking volatility of interest rates interact with the factors that create the Treasury yield curve. Doing so is crucial given that the shape of the curve is very indicative of expectations about long-term inflation. For example, Bianchi et al. (2009) as well as Mönch (2012) have shown that the higher the level of the curve, the higher the future inflation rate is expected to be. In parallel, others have linked the slope of the curve with monetary policy. They have established that the slope triggers fund rates and overnight rates (e.g., Diebold et al., 2006; Lange, 2013).

The second contribution is that our study adds to the literature dealing with uncertainty originating from central bank announcements, monetary surprises, and language and their possible outcomes and effects on long and short-term expectations (De Pooter et al., 2021; Hanson & Stein, 2015; Tillmann, 2020). In this study, we focus on the information content of interest rate uncertainty reflected in the prices of put and call options on U.S. Treasury futures, and how it affects the shape of the yield's term structure. Our major finding is that ambiguity about the path of future interest rates is a preceding indicator because interest rate uncertainty plays an important role in determining the future shape of the term structure in terms of its level, slope and curvature. We demonstrate that when interest rate uncertainty increases, the slope of the yield curve becomes steeper. This change indicates that the reaction of short-term yields is quick and more pronounced when the level of monetary policy uncertainty is high. This is an important point, given that investors adjust their investment strategies based on anticipated changes in interest rates, which in turn, can prompt fluctuations in the prices of assets such as stocks and commodities (e.g., Bauer et al., 2022; Idilbi-Bayaa & Qadan, 2021). In addition, this uncertainty can further influence not only expectations about inflation, but also exchange rates and capital flows, thereby affecting the overall stability of the economy.

Our findings also reveal a negative correlation between uncertainty and the curvature of the yield curve. A shock in uncertainty about interest rates leads to a decrease in the curvature factor. A plausible explanation for the negative relationship between uncertainty about interest rates and the curvature of the yield curve could be supply and demand. Heightened uncertainty is generally accompanied by a tendency to lower short-term nominal rates. Such a reduction prompts investors to rebalance their portfolios by buying longer-term Treasuries to safeguard the yields on their portfolios. Doing so leads to a hike in long-term bond prices, which in turn lowers the long-term Treasury yields and reduces the curvature of the yield curve.

Thus, a positive shock in the curvature factor corresponds to a more restrictive monetary policy, which is often associated with an impending recession.

These results have significant implications and applications for both practitioners and policymakers. The findings highlight that public expectations regarding monetary policy uncertainty are very important for the future evolution of interest rates. In a scenario of demand-driven inflation, central banks may strategically introduce ambiguity about the future trajectory of interest rates to restrain household consumption. This tactic leverages the documented negative correlation between interest rate uncertainty and consumption levels. Such uncertainty may increase due to changes in the tone of the language used by the Federal Open Market Committee (FOMC; Bauer et al., 2022; Gu et al., 2022; Szyszko et al., 2022), monetary policy surprises (e.g., Mumtaz & Zanetti, 2013; Tillmann, 2020) and announcements from central banks (e.g., Lamla & Vinogradov, 2019).

Thus, our results shed new light on the potential role of monetary policy uncertainty in the transmission of monetary policy to other mid- and long-term parts of the sovereign yield's term structure. In addition, they highlight that policymakers and money managers should keep a close eye on the evolution of this type of uncertainty, particularly because the shape of the term structure itself can be a policy target, given its direct impact on the real economy.

This study proceeds as follows. Section 2 outlines the scientific background. Section 3 describes the data. Section 4 presents the method. We report and discuss the empirical findings in Sect. 5 and conclude in Sect. 6.

2 Scientific background

The relationship between the term structure and interest rate uncertainty is rooted in several theoretical works. For example, the predictions of a two-factor framework combined with a general equilibrium approach suggested in Longstaff and Schwartz (1992) provide a comprehensive analysis of how interest rate volatility affects the term structure of interest rates within the broader context of an economy in equilibrium. They show that a two-factor model incorporating both the short-term interest rate and its volatility can effectively capture observed features such as humps and troughs, and the relationship between term premia and volatility. Lauterbach (1989) explores how fluctuations in consumption, production, and interest rate volatility affect investors' risk perceptions and preferences, leading to adjustments in the returns on Treasury bills and bonds to compensate for increased uncertainty and risk.

Many recent theoretical and empirical studies refer to the New Keynesian framework, where heightened uncertainty regarding interest rates functions as a negative demand shock, and contend that the uncertainty surrounding interest rates plays a crucial role as a macroeconomic indicator. For example, Mumtaz and Zanetti (2013) reveal that increased volatility in monetary policy leads to cautious behavior, affecting consumption and investment decisions, and ultimately exerting downward pressure on inflation and short-term interest rates. Sinha (2016) highlights that heightened uncertainty surrounding interest rate changes can lead to reductions in investment and consumption, dampening aggregate demand and subsequently suppressing inflationary pressures. Cremers et al. (2021) demonstrate that an increase in interest rate uncertainty forecasts a downturn in macroeconomic activity and heightened macroeconomic volatility.

Central banks typically adhere to the Taylor rule, adjusting nominal interest rates in response to expected inflation and output innovations. Given the Phillips curve's link between output fluctuations and inflation, declines in both inflation and output growth lead central banks to reduce short-term interest rates. Therefore, an increase in interest rate uncertainty is associated with reductions in nominal short-term interest rates, resulting in an increased slope of the yield curve.

Our results also show a negative relationship between interest rate uncertainty and the curvature of the yield curve. Thus, heightened uncertainty about interest rates is associated with a low degree of curvature. This finding accords with numerous studies contending that a decrease in the curvature, manifested in an inverted or flattened yield curve, indicates a subsequent decrease in future output growth and signifies a heightened likelihood of recession (e.g., Chauvet & Senyuz, 2016; Erdogan et al., 2015; Hasse & Lajaunie, 2022; Rudebusch & Williams, 2009).

Studies have used various proxies to capture interest rate uncertainty. For example, Chuderewicz (2002) uses interest rate uncertainty quantified from a GARCH (1,1) model of U.S. T-bills. Carlson et al. (2005) use a proxy for implied volatility computed from options on Federal funds futures. Swanson (2006) calculates monetary policy uncertainty as the width of the probability distribution of the Federal funds rate one year ahead, as implied by market prices on interest rate derivatives. Lahiri and Sheng (2010) utilize a survey-based measure. Mumtaz and Zanetti (2013) use a monetary structural vector autoregression and allow for the time-varying variance of monetary policy shocks. Baker et al. (2016) construct an overall economic uncertainty index based on the frequency of newspaper coverage. Sinha (2016) utilizes the standard deviation of the prices of call options on 30–90-day contracts for 2-year Treasuries as an ex-ante measure of interest rate uncertainty. Mueller, Tahbaz-Salehi and Vedolin (2017) use an implied volatility index based on information from one-month options on 30-year Treasury futures. Istrefi and Mouabbi (2018) define the uncertainty of interest rates as the sum of disagreements and the conditional volatility of mean forecast errors extracted from surveys. Kaminska and Roberts-Sklar (2018) calculate the implied volatility of interest rates based on options on short-term interest rate futures and use it as a proxy for interest rate uncertainty. Husted et al. (2020) construct a news-based index that captures the public's perceptions about Federal Reserve policy. Finally, Johri et al. (2022) use the time-varying volatility of the world's interest rates.

Recently, Bauer et al. (2022) gauged uncertainty regarding future short-term interest rates using a model-free measure derived from Eurodollar futures and options prices. Building on Husted et al.'s (2020) measure of monetary policy uncertainty about future short-term interest rates, Fasani et al. (2023) explored the potential outcomes of future monetary policy uncertainty on firms' decisions to enter or exit the market.

Unlike these studies, we use a VIX-style estimate of the expected 30-day volatility of the 10-year U.S. Treasury Note. Early in the 2000s, the CBOE launched an index called the CBOE Treasury Yield VIX Index (the TYVIX). It represents the expected future volatility of the Treasury bond market and is used in the literature as a proxy for the bond's market risk. In other words, the greater the uncertainty around changes in interest rates, the higher the TYVIX is.

Using this type of uncertainty factor, López, Sevillano and Jareño (2022) show that the TYVIX is informative for predicting the future performance of U.S. stocks. Using the TYVIX as a U.S. bond-market risk index, Sarwar (2022) establishes its negative correlation with the U.S. stock market. López (2015) finds that changes in U.S. Treasury bond volatility indices—computed using the market prices of 5-, 10- and 30-year Treasury futures options—are positively correlated with changes in both Treasury yield rates and U.S. non-fixed income and European equity-based volatility indices. Furthermore, changes in Treasury yield rates Granger cause changes in bond volatility. Finally, past changes in bond volatility help explain current changes in equity-based volatility indices and vice versa.

Earlier theoretical and empirical studies have also investigated the prediction power of interest rate uncertainty. For example, David and Veronesi (2014) establish a positive relationship between the implied volatility of the Treasury market and recessions, uncertainty about inflation and the probability of deflation. In addition, Bretscher et al. (2018) show that interest rate volatility implied from Treasury options predicts several macroeconomic and financial variables such as output, employment and aggregate investment.

Other studies have explored various aspects of the effect of monetary policy on interest rates and related economic behaviors. Cochrane and Piazzesi (2002) report that a 100-basis point increase in the one-month Eurodollar rate around the time of a change in the Federal funds target is followed by a 52-basis point increase in 10-year nominal Treasury yields. Mumtaz and Zanetti (2013) demonstrate that in response to an increase in monetary policy, uncertainty, output, inflation and the short nominal interest rate (the 3-month Treasury bill rate) all fall. Hanson and Stein (2015) reveal a significant effect of monetary policy surprises on long-term forward real rates. They observe that a 1% increase in the 2-year nominal yield on the day of the Federal Open Markets Committee's announcement leads to a 0.42% rise in the 10-year forward real rate.

Nakamura and Steinsson (2018) show that monetary shocks have strong and persistent effects on interest rates. Both nominal and real interest rates respond in tandem, experiencing an approximate one-to-one adjustment that extends over several years across the term structure. Tillmann (2020) finds that when there is a great deal of uncertainty about monetary policy, a policy shock causes a smaller upsurge in long-term yields compared to events with less uncertainty. De Pooter et al. (2021) demonstrate that the reactions of long-term nominal and real yields to monetary shocks are affected by the level of uncertainty about monetary policy. When there is little uncertainty, the effect of a monetary policy shock on yields is more pronounced. Bauer et al. (2022) find that both nominal and real long-term interest rates rise following an increase in uncertainty about monetary policy. Nevertheless, despite this attention, the literature still lacks comprehensive attempts to understand the dynamic relationships between the implied volatility of U.S. bond yields and the shape of the yield curve.

3 Data

As previously stated, we decomposed the U.S. Treasury yield curve into three components: the level, slope and curvature. To do so, we followed the procedures of Nelson and Siegel (1987) and used monthly data from the FRED database (https://fred.stlouisfed.org/) about 10 different yield maturities: 3 months, 6 months, 1 year, 2 years, 3 years, 5 years, 7 years, 10 years, 20 years and 30 years. To capture the volatility of U.S. treasury bonds, we used the CBOE's Treasury Yield VIX Index (TYVIX)—a VIX-style estimate of the expected 30-day volatility of 10-year U.S. Treasury Notes. This information also came from the FRED database. Table A1 in the Online Appendix reports the descriptive statistics of the latent factors and the volatility of the bonds.

The proxy utilized to reflect uncertainty about interest rates is the CBOE's 10-Year Treasury Note Volatility Futures. It is computed using the following formula suggested by the CBOE and rooted in the studies of Neuberger (1990) and Carr and Madan (2001):

$$\mathrm{TYVIX} = 100 \times \sqrt{\frac{365}{30} \cdot \frac{1}{\tau}\left[2e^{rt}\left\{\sum_{k_i} \frac{\Delta K_i}{K_i^2}\mathrm{Price}_{Ki} + \sum_{k_j} \frac{\Delta K_j}{K_j^2}\mathrm{Price}_{Kj}\right\} - \left(\frac{F}{K_{ATM}} - 1\right)^2\right]}. \tag{1}$$

$\frac{365}{30}$ translates the one-month variance into annualized variance terms; τ denotes the time to expiration; r is the risk-free interest rate to expiration; ΔK is the strike interval associated with K; Price_{K_I} is the mid-quotes of out-of-the-money puts and calls with strike values K_i and K_j, respectively. Similarly, it denotes the average of the mid-quotes of the at-the-money (ATM) put and call. F is the forward index level.

The volatility of interest rates is not constant over time. Figure 2 depicts the evolution of the TYVIX from January 2003 to April 2020 and shows that interest rate volatility spikes in the periods surrounding financial crises, such as the subprime crisis, the European sovereign debt crisis and the COVID-19 outbreak. Periods of significant interest rate volatility tend to spark intensive debates in the literature on the possible drivers (e.g., Omrane & Savaşer, 2017). Given that interest rate uncertainty by itself can negatively affect economic activity (Cremers et al., 2021), understanding its determinants and its link with the shape of the yield curve is important.

Figure 1 depicts the temporal changes in the latent factors alongside the TYVIX throughout the sample period. Specifically, Fig. 1a shows the evolution of both the TYVIX and the level bond yield factor. Figure 1b illustrates the co-movements of the TYVIX and the slope factor, and Fig. 1c depicts the evolution of the TYVIX with the curvature factor. A quick glance at the figure reveals a positive correlation between the VIX-style bond measure and both the level and slope of the yield curve. The correlation is 0.449 (t-stat. = 7.21) between the TYVIX and the level and 0.582 (t-stat. = 10.28) between the TYVIX and the slope.

On the other hand, there is a negative correlation between the uncertainty measure and the curvature factor. The correlation is −0.439 (t-stat. = −7.02). Higher levels of uncertainty about interest rates coincide with a lower degree of curvature.

Table 1 Stationarity tests results

	ADF			Phillips Perron			KPSS		
	Level	Δ	I(d)	Level	Δ	I(d)	Level	Δ	I(d)
TYVIX	−3.31b	−12.66a	I(0)	−3.09b	−15.61a	I(0)	0.59b	0.05a	I(0)
Level factor	−1.16	−13.85a	I(1)	−1.21	−13.85a	I(1)	1.65	0.05a	I(1)
Slope factor	−1.50	−13.80a	I(1)	−1.66	−13.84a	I(1)	0.25	0.09c	I(1)
Curvature factor	−2.20	−8.29a	I(1)	−1.99	−15.45a	I(1)	0.30	0.11	I(1)
IP	−1.38	−3.13b	I(1)	−1.90	−3.12b	I(1)	0.65	0.24	I(1)
CPI	−1.34	−8.94a	I(1)	−1.35	−7.35a	I(1)	1.80	0.23	I(1)
STLFSI	−3.52a	−14.41a	I(0)	−3.45a	−14.45a	I(0)	0.12	0.08c	I(1)

The table reports the results of the stationarity tests. IP is industrial production; CPI is the Consumer Price Index and STLFSI is the St. Louis Financial Stress Index. Δ is the first natural logarithm difference of the variable, and an I(d) series is differenced d times to be I(0). Thus, I(0) denotes stationarity in level, while I(1) denotes stationarity in first difference. The augmented Dickey–Fuller (ADF), Phillips–Perron (PP) and Kwiatkowski–Phillips–Schmidt–Shin (KPSS) tests are employed to assess the presence of a unit root in these variables. The values of the tests are the t-statistics, and "a", "b", and "c" denote statistical significance at the 1%, 5% and 10% levels, respectively

Similarly, lower levels of uncertainty are associated with a higher curvature in the yield curve. These results are aligned with the New Keynesian framework, where an increase in uncertainty about interest rates acts as a negative demand shock, resulting in a decrease in both inflation and interest rates (Sinha, 2016).

Our results hold true using other proxies for the level, slope and curvature. Figure A1 in the Online Appendix shows the evolution of the TYVIX with an alternative proxy for the latent factors. The proxy for the level factor is derived by calculating the average of the yields. The proxy for the slope factor is established by measuring the difference between the yields of long-term and short-term bonds. Finally, the proxy for the curvature factor is determined by taking twice the yield on 3-year bonds minus both the yields on both 3-month and 30-year bonds (i.e., $2 \times Y_3 - Y_{3M} - Y_{30}$).

4 Methods

4.1 Computing the level, slope and curvature

We computed the three latent factors of the yield curve using Nelson and Siegel's (1987) framework. We also followed Diebold et al.'s (2006) suggestion to use maximum likelihood and a Kalman filter. Thus, our first equation states:

$$y_t(\tau) = \beta_{1,t} + \beta_{2,t}\left(\frac{1 - e^{-\lambda\tau}}{\lambda\tau}\right) + \beta_{3,t}\left(\frac{1 - e^{-\lambda\tau}}{\lambda\tau} - e^{-\lambda\tau}\right), \tag{2}$$

where $y_t(\tau)$ is the set of yields at each maturity (τ). $\beta_{1,t}$, $\beta_{2,t}$ and $\beta_{3,t}$ are time-varying parameters and λ is the exponential decay rate. The loadings of parameter $\beta_{1,t}$ is one

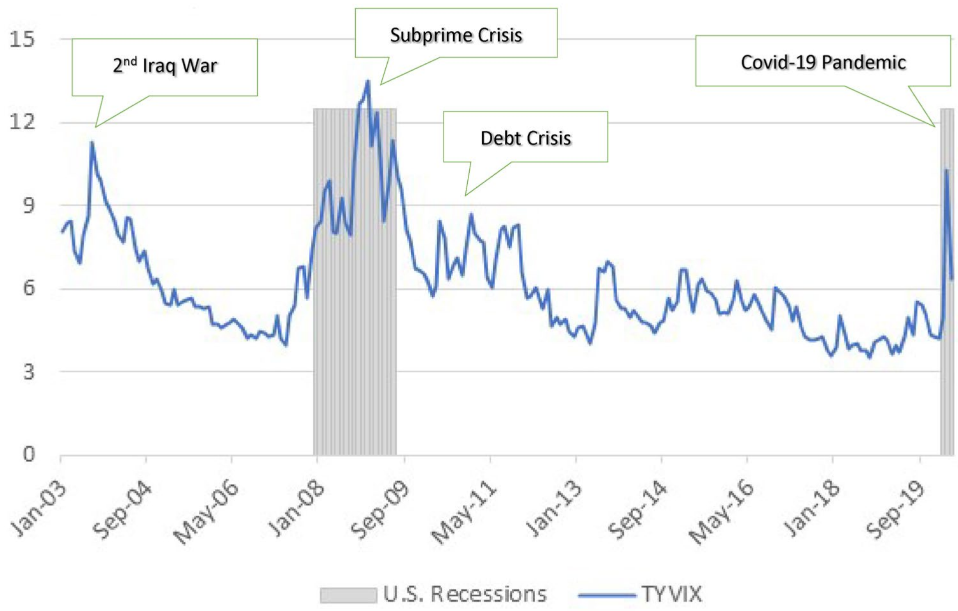


Fig. 2 Evolution of the uncertainty about interest rates over time (TYVIX). *Notes*: The figure depicts the evolution of the VIX-style estimate of the expected 30-day volatility of the 10-year U.S. Treasury Note. We used this measure as a proxy for interest rate uncertainty. The vertical axis is the perceived risk in standard deviation terms. Shaded areas indicate U.S. recessions. The data come from the FRED database (https://fred.stlouisfed.org/) and the recessionary periods are determined by the National Bureau of Economic Research (NBER)

for all maturities. Hence, it is associated with the long end of the curve and viewed as the level factor (L_t). The loading of parameter $\beta_{2,t}$ starts at one and decays with the maturities. Hence, it is viewed as the short-term factor and interpreted as the slope (S_t). The loading of $\beta_{3,t}$ starts at zero, increases and then decays to zero again. Hence, it is viewed as a medium-term parameter and interpreted as the curvature factor (C_t) as follows:

$$y_t(\tau) = L_t + S_t\left(\frac{1 - e^{-\lambda\tau}}{\lambda\tau}\right) + C_t\left(\frac{1 - e^{-\lambda\tau}}{\lambda\tau} - e^{-\lambda\tau}\right). \tag{3}$$

Diebold et al. (2006) suggest extending the form by letting L_t, S_t and C_t follow a first-order vector autoregressive process as follows:

$$\begin{pmatrix} L_t - \mu_L \\ S_t - \mu_S \\ C_t - \mu_C \end{pmatrix} = \begin{pmatrix} a_{11}a_{12}a_{13} \\ a_{21}a_{22}a_{23} \\ a_{31}a_{32}a_{33} \end{pmatrix}\begin{pmatrix} L_{t-1} - \mu_L \\ S_{t-1} - \mu_S \\ C_{t-1} - \mu_C \end{pmatrix} + \begin{pmatrix} \eta_t(L) \\ \eta_t(S) \\ \eta_t(C) \end{pmatrix}. \tag{4}$$

In the following equation, N is the observed yields regressed against the level, slope and curvature:

$$\begin{pmatrix} y_t(\tau_1) \\ y_t(\tau_2) \\ \cdot \\ \cdot \\ y_t(\tau_N) \end{pmatrix} = \begin{pmatrix} 1 & \frac{1-e^{-\lambda\tau_1}}{\lambda\tau_1} & \frac{1-e^{-\lambda\tau_1}}{\lambda\tau_1} - e^{-\lambda\tau_1} \\ 1 & \frac{1-e^{-\lambda\tau_2}}{\lambda\tau_2} & \frac{1-e^{-\lambda\tau_2}}{\lambda\tau_2} - e^{-\lambda\tau_2} \\ & \vdots & \\ & \vdots & \\ 1 & \frac{1-e^{-\lambda\tau_N}}{\lambda\tau_N} & \frac{1-e^{-\lambda\tau_N}}{\lambda\tau_N} - e^{-\lambda\tau_N} \end{pmatrix}\begin{pmatrix} L_t \\ S_t \\ C_t \end{pmatrix} + \begin{pmatrix} v_t(\tau_1) \\ v_t(\tau_2) \\ \cdot \\ \cdot \\ v_t(\tau_N) \end{pmatrix}. \tag{5}$$

We can write the last equation in matrix notation:

$$(f_t - \mu) = A(f_{t-1} - \mu) + \eta_t, \tag{6}$$

$$y_t = \Lambda f_t + v_t, \tag{7}$$

where f_t is a 3×1 vector of the latent factors, and μ_L, μ_S and μ_C are the mean values of the level, slope and curvature. "A" is a 3×3 vector of coefficients. y_t is a $N\times1$ vector of observed yields (τ) at time t and Λ is a $N\times3$ matrix of factor loadings. We assumed a white noise distribution for the disturbances η_t and v_t. They are orthogonal to each other as described in Eq. (8):

$$\begin{pmatrix} \eta_t \\ v_t \end{pmatrix} \sim WN\left[\begin{pmatrix} 0 \\ 0 \end{pmatrix}, \begin{pmatrix} Q & 0 \\ 0 & H \end{pmatrix}\right], \tag{8}$$

$$E(f_0, \eta_t') = 0, \tag{9}$$

$$E\left(f_0, v_t'\right) = 0, \tag{10}$$

where Q is the matrix of the variance–covariance of transition in Eq. (6) and H is the variance–covariance matrix of the sixth equation. We assumed that the yields of the maturities are uncorrelated, meaning that the H matrix is diagonal. In addition, we allowed the latent factors to be correlated. Thus, matrix Q is a non-diagonal matrix. In our study, we adopted the opposite approach to the sign of the slope factor from Nelson and Siegel (1987) and Diebold et al. (2006). We measured the slope as long-term yields minus short-term yields.

4.2 Granger causality

We conducted a Granger (1980) causality test to examine whether uncertainty about interest rates ($\sigma_{B,t}$) Granger-cause the components of the yield curve (L_t, S_t, C_t) and vice versa. If this association holds true, then lagged values of $\sigma_{B,t}$ should contain information that helps predict $Y_t = [L, S, C]$. This relationship can be formulated as follows:

$$\begin{pmatrix} Y_t \\ \sigma_{B,t} \end{pmatrix} = \begin{pmatrix} \beta_{10} \\ \beta_{20} \end{pmatrix} + \begin{pmatrix} \beta_{11} & \alpha_{11} \\ \alpha_{21} & \beta_{21} \end{pmatrix} \begin{pmatrix} Y_{t-1} \\ \sigma_{B,t-1} \end{pmatrix} + \begin{pmatrix} \beta_{12} & \alpha_{12} \\ \alpha_{22} & \beta_{22} \end{pmatrix} \begin{pmatrix} Y_{t-2} \\ \sigma_{B,t-2} \end{pmatrix} + \cdots + \begin{pmatrix} \beta_{1k} & \alpha_{1k} \\ \alpha_{2k} & \beta_{2k} \end{pmatrix} \begin{pmatrix} Y_{t-k} \\ \sigma_{B,t-k} \end{pmatrix} + \begin{pmatrix} \psi_{1t} \\ \psi_{2t} \end{pmatrix}. \tag{11}$$

The level, slope and curvature are calculated as described in Sect. 4.1. “k” in Eq. (11) denotes the length of the lag and ψ_t is the error term. Formally, if the hypothesis that $\alpha_{11} = \alpha_{12} = \cdots = \alpha_{1k} = 0$ is rejected, then lagged values of uncertainty help explain the current values of the curve’s components. On the other hand, if we do not reject this hypothesis, then the interest rate uncertainty variable does not Granger-cause the other variable. We used this model for the causal relationships between σ_B and each of the curve’s components.

5 Empirical findings

Table 1 reports the results of the unit root tests. We tested the stationary of the variables using the augmented Dickey and Fuller (ADF, 1979), Phillips and Perron (1988) and Kwiatkowski–Phillips–Schmidt–Shin (KPSS) tests. I(0) denotes stationarity in level, while I(1) denotes stationarity in first difference. Remarkably, the variables TYVIX and St. Louis Financial Stress Index (STLFSI) exhibit significant MacKinnon (1996) statistics at the level, signifying the rejection of the null hypothesis of non-stationarity. This result suggests that these variables are stationary in the level. On the other hand, the level factor, the slope, the curvature, the industrial production (IP) and the CPI variables demonstrate stationarity in the first difference.

Table 2 reports the results of the Granger (1980) causality test between interest rate uncertainty (captured using the TYVIX) and the three latent factors. The

Table 2 Feedback effects between the bond VIX and the latent factors

	K = 1	K = 2	K = 3	K = 4	K = 5	K = 6	K = 7	K = 8	K = 9	K = 10
Panel A—The TYVIX and the level factor of the yield curve										
TYVIX ↛ Level	0.02	0.02	1.30	3.01b	2.98b	3.87a	3.19a	2.94a	2.98a	2.66a
Level ↛ TYVIX	2.01	0.79	0.98	0.97	0.85	1.00	1.06	0.78	0.63	0.52
Panel B—The TYVIX and the slope factor of the yield curve										
TYVIX ↛ Slope	10.43a	6.09a	5.57a	4.20a	4.4a	4.39a	3.49a	2.92a	3.03a	2.53a
Slope ↛ TYVIX	0.16	0.09	0.27	0.26	0.70	0.82	0.83	1.15	1.44	1.19
Panel C—The TYVIX and the curvature factor of the yield curve										
TYVIX ↛ Curvature	2.09	1.04	0.85	0.98	0.83	0.71	2.01c	1.91c	1.99b	1.88c
Curvature ↛ TYVIX	1.44	0.88	0.47	1.09	0.81	1.16	0.93	1.08	1.12	1.29

Panel A illustrates the results of the Granger-causality test between the level factor of the yield curve and the volatility of the bonds. Panel B illustrates the results between the slope factor and the volatility of the bonds. Panel C illustrates the results between the curvature factor and the volatility of the bonds. By A ↛ B we mean that "A" does not Granger-cause B. "a", "b" and "c" denote statistical significance at the 1%, 5% and 10% levels, respectively

underlying hypothesis in the first row of Panel A states that interest rate uncertainty does not Granger-cause the yield level factor. We denote this relationship as TYVIX ↛ Level. The significant F-statistic indicates that we should reject the null hypothesis of a non-causal relationship. Rejecting the null hypothesis implies that the TYVIX is useful in predicting the level of the yield curve. We detected a significant rejection of the null hypothesis starting from the fourth lag (k = 4), as evident by the statistically significant F-statistic values.

The second row of Panel A reports the results of the alternative hypothesis. It posits that the level of interest rates Granger-cause interest rate uncertainty. The results indicate that "Level" does not Granger-cause the TYVIX, as evident by the insignificant F-statistic values. In other words, past values of the level factor fail to predict future values of interest rate uncertainty.

The first row in Panel B of Table 2 presents the results of the hypothesis that the TYVIX does not Granger-cause the slope (TYVIX ↛ Slope). The second row reports the results of the parallel hypothesis that the slope does not Granger-cause the TYVIX (Slope ↛ TYVIX). The results show significant F-statistic values starting from the first lag. This finding indicates that interest rate uncertainty provides valuable insights for forecasting the yield curve's slope. On the other hand, the insignificant F-statistic values in the second row of Panel B suggest that past values of the slope factor do not predict future values of the TYVIX.

Panel C of the table reports the F-statistic values of the pairwise Granger-causality test examining the relationship between interest rate uncertainty and the curvature of the yield curve. In the first line, we observe significant F-statistic values starting from the seventh lag. However, the insignificant F-statistic values in the second line show that the curvature does not Granger-cause the TYVIX.

Table A2 in the Online Appendix follows the same procedure and reports the Granger-causality test results between the TYVIX and proxies for the latent factors: a proxy for the level, which is calculated as the average of the yields, a proxy for the

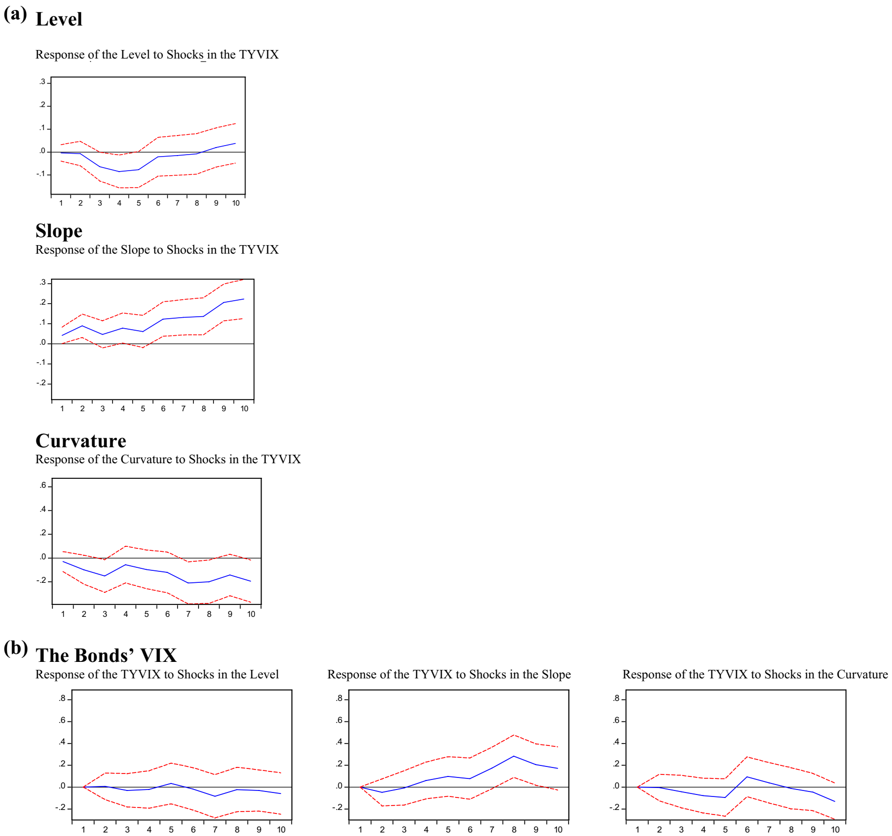


Fig. 3 Impulse responses: **a** level, slope and curvature, **b** The Bonds' VIX. *Notes*: The figure plots the impulse responses of the level, slope and curvature with the VIX-style estimate of the expected 30-day volatility of the 10-year US Treasury Note

slope, which is the spread between the yields of long- and short-term bonds, and a proxy for the curvature, which is computed as twice the yields on 3-year bonds minus those on 3-month and 30-year bonds ($2 \times Y_3 - Y_{3M} - Y_{30}$).

Table A3 in the Online Appendix reports the results of the Granger-causality test between the simple difference of the TYVIX and the three latent factors. Table A4 in the Online Appendix examines the Granger-causality test between the first difference (logarithmic difference) of the TYVIX and the three latent factors.

The results of the Granger-causality tests are also reinforced using the impulse response function. Figure 3 (i.e., a, b) plots the impulse responses of the latent factors to shocks in interest rate uncertainty and vice versa. Figure 3a shows that a shock in interest rate uncertainty is followed by a decrease in the level factor. More importantly, Fig. 3a indicates that shocks to interest rate uncertainty are followed by an increase in the slope. One plausible explanation for this spike in the slope is simply the rapid reduction in short-term interest rates imposed by the central bank.

Qadan, Shuval and David (2023) note that fluctuations in interest rate uncertainty can signal future changes in economic activity due to their impact on hedging costs.

The results align with previous studies confirming the effect of uncertainty about the monetary policy on short- and long-term interest rates. For example, Mumtaz and Zanetti (2013) indicate that more uncertainty about monetary policy is associated with a corresponding decrease in the short-term nominal interest rate. Others have demonstrated that uncertainty about monetary policy leads to a rise in long-term interest rates. Cochrane and Piazzesi (2002), for example, documented that 10-year nominal Treasury yields rise in response to an increase in monetary policy uncertainty. Hanson and Stein (2015) established the strong impact of monetary policy shocks on the 10-year forward real rate. Tillmann (2020) determined that during periods of heightened monetary policy uncertainty, a policy shock triggers a less pronounced increase in long-term yields compared to events involving less uncertainty. Bauer et al. (2022) established that both nominal and real long-term interest rates experience an upswing following an escalation in monetary policy uncertainty.

More in-depth investigation of the effect of the shocks on the latent factors shows that uncertainty about interest rates not only drives the slope, but also drives the curvature of the yield. Figure 3a indicates that a shock in interest rate uncertainty is followed by a decrease in the curvature factor. This result is in line with the fact that increased uncertainty typically leads to an inclination towards reducing short-term nominal interest rates. This change prompts investors to adjust their investment portfolios by allocating more of their assets to longer-term Treasuries to prevent a significant reduction in portfolio yields. This adjustment results in an increase in the prices of long-term bonds, subsequently causing a decrease in long-term Treasury yields and a flattening of the yield curve.

Figure 3b shows the impulse responses of interest rate uncertainty to shocks in the latent factors. The resulting picture accords with the results of the Granger-causality tests. Thus, shocks to the three latent factors do not have any significant effect on uncertainty about interest rates.

We used the autoregressive distributed lag (ARDL) procedure to explore the nature of the association between interest rate uncertainty and the innovations in the shape of the yield curve. This is an ordinary least squares (OLS) model, which is applicable for both non-stationary time series as well as for times series with a mixed order of integration (Pesaran & Shin, 1995). This model takes enough lags to capture the data generating process in a general-to-specific modeling framework.

We used the following models to capture the long-term relationship between the variables of interest:

$$Level_t = a + \sum_i^I b_i Level_{t-i} + \sum_j^J c_j TYVIX_{t-j+1} + \psi' Control_t + u_t. \tag{12}$$

$$Slope_t = a + \sum_i^I b_i Slope_{t-i} + \sum_j^J c_j TYVIX_{t-j+1} + \psi' Control_t + u_t. \tag{13}$$

$$Curvature_t = a + \sum_i^I b_i Curvature_{t-i} + \sum_j^J c_j TYVIX_{t-j+1} + \psi' Control_t + u_t. \tag{14}$$

The level, slope and curvature are the three latent factors of the yield curve. TYVIX is the CBOE's 10-Year Treasury Note Volatility Futures Index that captures the uncertainty in the U.S. bond market. The control variables are the natural logarithm values of industrial production ($Log(IP_t)$), the CPI ($Log(CPI_t)$) and the St. Louis Financial Stress Index (STLFSI). In Fig. 4 we depict the Akaike Information Criteria (AIC) that result from running Models 10–12 with different lags. The optimal AIC results are achieved using (K, J = 4, 6) for Model (10); (K, J = 1, 9) for Model (11); and (K, J = 5, 9) for Model (12). Other ARDL specifications appear in the Online Appendix in which we include the yield curve factors as explanatory variables (see Fig. A2 in the Online Appendix).

Finally, we assessed the stability of the parameters in the selected models and tested for possible structural breaks between the variables of interest over time. We used Brown et al.' (1975) cumulative sum test (CUSUM), which is based on the cumulative sum of the recursive residuals. Figure 5 plots the cumulative sum together with the 5% critical lines. Generally, the test finds parameter instability if the cumulative sum goes outside the area between the two critical (dotted red) lines. The results of the CUSUM stability test reject the hypothesis of structural breaks. They confirm that the parameters are stable over time in the different model specifications of the ARDL specification we used. For robustness, we conducted Bai–Perron's (1998) test. In general, the findings consistently support the notion of parameter stability throughout the entire period except for the subprime crisis in 2008. A plausible explanation for this breakpoint specifically in 2008 is the severe economic circumstances coupled with the downfall of numerous financial institutions both in the US and around the globe. The results are reported in Table A5 in the Online Appendix.

For robustness checks, we added the yield curve factors as explanatory variables in Eqs. 10–12. Figures A2 and A3 in the Online Appendix show the results of the Akaike information criteria and the cumulative sum of the recursive residuals, respectively. In addition, we repeated the tests regarding the role of interest rate uncertainty in shaping the entire yield term structure with a focus on the role of the uncertainty originating from very long-term bonds. To do so, we computed the VIX reflecting the forward-looking volatility on bonds with maturities exceeding 20 years. Technically speaking, we used data on options written on the 20 + Year Treasury Bond ETF (TLT). This fund follows the performance of an index consisting of U.S. Treasury bonds with maturities exceeding 20 years. We obtained the data on these options from http://www.deltaneutral.com/. We then computed the VIX index using the formula suggested in the CBOE's White Paper. The resulting VIX-style measure captures the uncertainty surrounding Treasury yields with maturities exceeding 20 years. Thus, we developed a measure of long-term interest rate uncertainty and denoted it as VIX_{20}.

Table A6 reports the results of the Granger (1980) causality test examining the feedback effect between the VIX_{20} and the three latent factors. The findings indicate that while the VIX_{20} does not Granger-cause the level factor, the level does

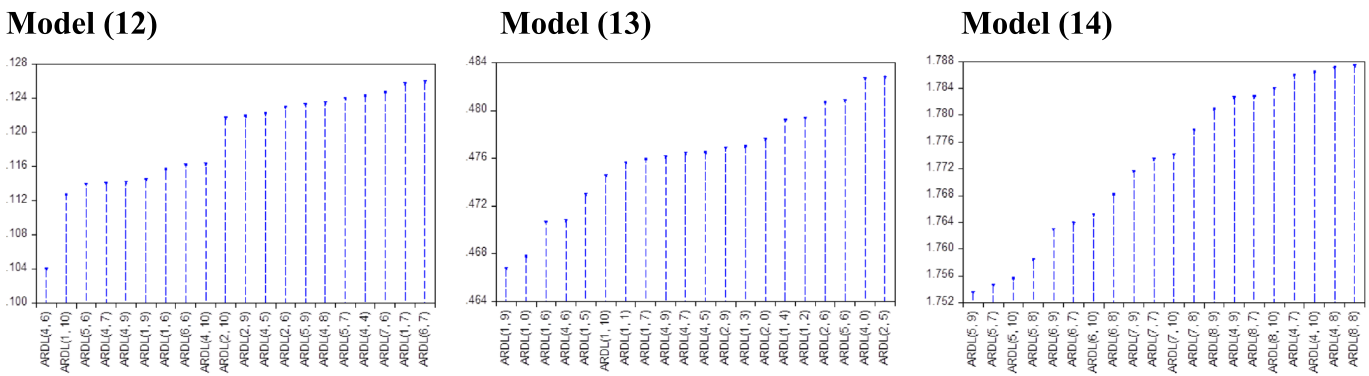


Fig. 4 Akaike Information Criteria. *Notes*: The figure depicts the Akaike Information Criteria that result from regressing the specific curve factor against lagged distributed values of the selected variable and lagged values of interest rate uncertainty. The control variables include the natural logarithm values of industrial production, the CPI and the St. Louis Financial Stress Index

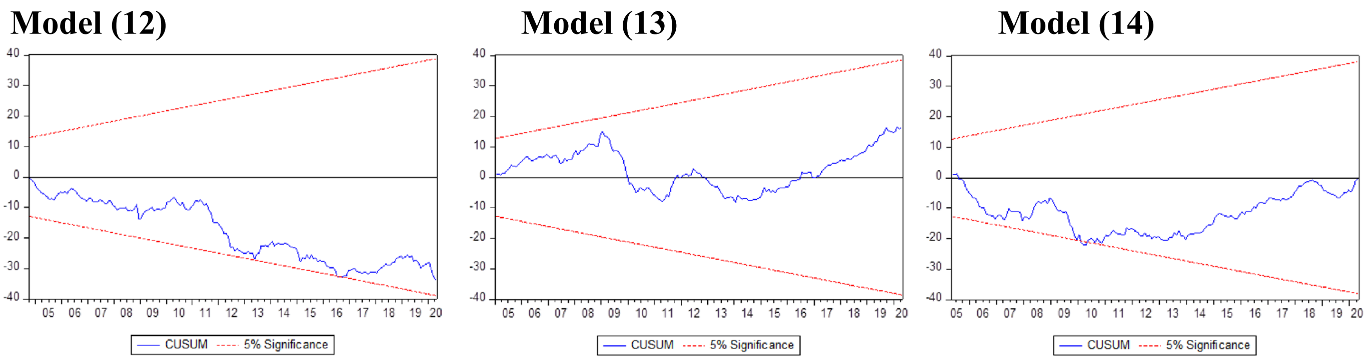


Fig. 5 The Cumulative Sum of the Recursive Residuals. *Notes*: The figure plots the cumulative sum of the recursive residuals stemming from the cumulative sum test (CUSUM) suggested by Brown et al. (1975). The continuous line plots the cumulative sum together with the 5% critical lines denoted by the dotted red lines. If the cumulative sum goes outside the area between the two critical lines, it indicates parameter instability. The cumulative sum of the three models (M9–M11) fails to cross the critical (dotted) lines

Granger-cause the VIX_{20}, as evident in the significant F-statistic values at the sixth, seventh and eighth lags. Nevertheless, the F-statistics values are relatively small and reflect relatively low confidence levels. Panel B of the table, however, reveals that the VIX_{20} has a significant effect on the slope of the yield curve, as evident from the significant Granger-causality results. The uncertainty surrounding long-term interest rates is a significant driver of the slope from the first lag, but not vice versa. Finally, Panel C of the table shows that the VIX_{20} Granger-causes the curvature factor, as evident in the first to the third lag, and the curvature Granger-causes the VIX_{20} starting from the sixth lag. Figure A5 in the Online Appendix illustrates these relationships.

To conclude, regardless of the time span of the bond maturity used to capture the uncertainty about interest rates, we find that this uncertainty imbedded in both 10-year and 20 + year bonds drive the shape of the yield curve in the same direction. As previously stated, the shape of the term structure itself can be a policy target, given its possible implications for the macroeconomy.

6 Conclusions

The implications of the interaction between the yield curve and economic growth have been studied extensively, both empirically and theoretically. Nevertheless, the interactions between the uncertainty about interest rates and the shape of the yield curve and their implications are still unexplored. In this study, we helped fill this gap by examining the information content of the uncertainty about interest rates reflected in the prices of put and call options on U.S. Treasury futures, and how such uncertainty affects the shape of the sovereign yield curve.

Our findings can be summarized as follows. First, fluctuations in interest rate uncertainty play a crucial role in shaping the yield curve. Uncertainty about interest rates has a positive effect on the slope of the yield curve. Such uncertainty tends to rise sharply during economic crises and is accompanied by an increase in the slope of the yield curve, resulting from the immediate response of short-term interest rates relative to long-term interest rates. On the other hand, a reduction in uncertainty surrounding interest rates is accompanied by a decrease in the slope of the yield curve. Second, the results indicate a negative association between uncertainty and both the level and curvature of the yield curve. As discussed in the literature, a positive shock to the curvature factor corresponds to a more stringent monetary policy that is associated with an upcoming recession.

Theoretically, we related these results to the New Keynesian framework where an increase in the uncertainty about interest rates acts as a negative demand shock leading to a decrease in investment and consumption. This cautious approach may impede economic growth and lead to a drop in inflation as well as short-term interest rates.

Our results suggest that the responses of the yield curve to fluctuations in the forward-looking volatility of interest rates are relatively quick. In addition, expectations about future rates are particularly sensitive to high levels of uncertainty about monetary policy. Understanding the role of interest rate uncertainty in designing the shape of the term structure is important for academics, traders, and policymakers.

Our findings raise the possibility that interest rate uncertainty might have different consequences for a wide range of sectors comprising the economy. Thus, a promising avenue for future investigation would be to study the influence of interest rate uncertainty on exchange rates, capital flows, and other macro-financial variables that affect the overall stability of the economy. We leave this potential investigation for future research.

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Declarations

Conflict of interest The authors have not disclosed any conflict of interest.

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