USD interest rate swaption strategies during the unconventional monetary policy and pandemic eras

Hiroaki Shirokawa*[1], Kohei Yamaguchi†[1], Takahiro Obata‡[1], and Ryuta Sakemoto§[2]

[1] *Asset Management One Co. Ltd., Tokyo, Japan.*

[2] *Hokkaido University, Hokkaido, Japan.*

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Abstract

This study investigates the performance of USD interest rate swaption straddle strategies during the unconventional monetary policy and pandemic eras. We construct long-short portfolio swaption straddles using longer tenors and maturities than those in the previous literature. Moreover, we propose the equally weighted strategy that takes risk exposures to both volatility and jump risks. This strategy generates a higher Sharpe ratio than the delta-gamma neutral strategy during the unconventional monetary policy period. This result is weakly associated with spot swap forward rate jumps and robust including transaction costs. We also observe that adopting longer maturity swaptions in the long position leads to higher values of risk and returns.

Keywords: Swaptions, Long-short portfolios, Term structure, USD interest rate market

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*E-mail: hiroaki.shirokawa@am-one.co.jp

†E-mail: kohei.yamaguchi@am-one.co.jp

‡E-mail: takahiro.obata@am-one.co.jp

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1. Introduction

Derivatives are important tools for investors' risk management. In particular, the market size of interest rate derivatives is large and impacts global financial markets. The Bank for International Settlements (BIS) reports that the notional value of the outstanding interest rate derivatives was more than 450 trillion US dollars at the end of 2021. The prices of interest rate derivatives depend on volatility in the market, and understanding volatility risk is essential for investors.

Volatility risk has been investigated by both academia and the financial industry. The important work of Bakshi and Kapadia (2003) finds a negative volatility risk premium, which suggests that implied volatility is larger than realized volatility. Volatility risk in the bond market is a relatively new research agenda because variance swaps in interest rates are traded over-the-counter (OTC), and the benchmark of implied volatility in the bond market does not have a long historical record (Mele and Obayashi, 2013; Duyvesteyn and de Zwart, 2015; hereafter DZ, 2015).[1] Implied volatility in the bond market has distinct information from that in the stock market. Mele et al. (2015) present empirical evidence that jump did not concentrate on the global financial crisis (GFC). Byun and Chang (2015) suggest that financial institutions are primary traders in the bond market and prefer to take volatility risks. This market structure differs from equity and currency markets, where individual and corporate investors actively trade. It is essential for traders in the bond market to find methodologies that generate profits using volatility risk.

This study proposes a new strategy in the USD interest rate swaption market. We employ the approach proposed by Cremers et al. (2015), who construct a long-short combination of at-the-money (ATM) straddles in the swaption market. Moreover, DZ (2015) adopt Cremers et al.'s (2015) approach and propose the delta-gamma (delta-vega) neutral strategy to insulate jump (volatility) risk.[2] We extend the work of DZ (2015) in the following six points. First, we explore effects of maturities and tenors on

[1] The USD interest rate swaption represents a large market. According to the Commodity Futures Trading Commission (CFTC), the gross notional outstanding of the USD interest rate swaption in December 2023 was recorded as 13 trillion USD.

[2] Cremers et al. (2015) present that these two risks have distinct information and that both risk premiums are negative for cross-sectional stock pricing models. Chang et al. (2019) employ a closed-form option pricing formula and find the same results.

the long-short swaption straddle strategies. DZ (2015) employ a 10-year swaption tenor, sell swaption straddles for short maturities and buy swaption straddles for long maturities. They reveal that this long-short strategy yields positive returns, which implies that there exists a concave upward-sloping term structure in the volatility risk premium. Although DZ (2015) investigate maturities up to 1 year, we extend their analysis. This is because Trolle and Schwartz (2014) adopt maturities up to 10 years and reveal a downward-sloping function of the interest rate swap volatility across maturities, implying that the difference in volatility risks between short and long maturities widens. This finding suggests that extending maturities may increase returns for long-short swaption straddle strategies, since protection against volatility risk on longer maturities tends to be cheaper.

Second, we include a longer period of low interest rates and monetary policy uncertainty. The Federal Reserve Board (FRB) implemented unconventional monetary policies to mitigate the effects of the GFC in 2008, which led to lower interest rates (e.g., Bernanke, 2020). The new regulation was introduced after the GFC had impacted the swap market (Jermann, 2020). Moreover, a decline in option-based short rate uncertainty was clear after the GFC (Bauer et al., 2022). It is crucial for investors to explore whether swaption strategies proposed in the previous literature are still effective in the new era. Therefore, our sample encompasses a low interest rate period, and we focus on the period between March 2007 and April 2022.[3]

Third, we propose the equally weighted strategy that keeps the same weight for both long and short positions. DZ (2015) present empirical evidence that the delta-gamma (delta-vega) neutral strategy insulates jump (volatility) risk and takes only volatility (jump) risk. They report that the delta-gamma strategy achieves a high Sharpe ratio. However, this argument may not be applicable during unconventional monetary policy periods, because the monetary policy reduces uncertainty in interest rates, as suggested by Bernanke (2020) and Bauer et al. (2022), and hence implied volatilities of swap forward rates decline. Our equally weighted strategy takes exposures to jump risk and compensates for the decline in volatility risk. Our sample period also includes the COVID-19 pandemic period, when the forward rates jump due to an increase in the inflation pressure.

[3] In Online Appendix, we extend the data period to September 2023.

Fourth, we examine the relationships between profits of the equally weighted strategy and market state variables. It is essential for investors who implement the equally weighted strategy to know whether this strategy generates stable profits. We adopt state variables in the bond market and those obtained from other markets and real economic activities. In addition to established state variables in the bond market, we utilize proxies for uncertainty, as developed by recent works, such as those of Jurado et al. (2015), Baker et al. (2016), and Husted et al. (2020), which employ a large number of time series or text-based data.

Fifth, we assess the effects of delta hedges in long positions for the swaption straddles. The effectiveness of delta hedges in short positions is reported by Choi et al. (2017). However, it is still open whether they function in long positions. Long positions increase the profits as increases in implied volatility, because they carry the positive vega. Hence, we evaluate whether unhedged long positions yield a higher Sharpe ratio.

Finally, we evaluate the effects of transaction costs using bid and ask prices on normal volatility using Bloomberg. DZ (2015) demonstrate that transaction costs impact profitability of the long-short combination of straddles in the swaption market. However, many option traders adopt volatility trades in the 2010s and the transaction costs may have declined. Therefore, we explore whether the equally weighted strategy remains profits after considering transaction costs.

Our results are summarized in six points. First, our equally weighted strategy generates a higher Sharpe ratio than the delta-gamma neutral strategy during the same periods (0.76 vs 0.42), which is statistically significant based on Ledoit and Wolf's (2008) test.[4] Our equally weighted strategy takes exposures to both volatility risk and jump risk, as demonstrated by Cremers et al. (2015). However, the delta-gamma neutral strategy takes exposures to only volatility risk, suggesting that changes in implied volatility of swap forward rates lead to higher profits. Our results present that the unconventional monetary policy in the U.S. lowers swap forward rates and leads to a decline in uncertainty in the interest rate market, as suggested by Bernanke (2020) and Bauer et al. (2022). These market situations have negative impacts on the Sharpe ratio for the delta-gamma neutral strategy. In fact, DZ (2015)

[4]In this case, we employ a 10-year tenor with the swaption maturities of the short position being 3 months and those of the long position being 1 year.

report the Sharpe ratio for this strategy to be 0.95 before the unconventional monetary policy period, but it is 0.42 in our data period. The equally weighted strategy remains a higher Sharpe ratio due to taking exposures to jump risk. In other words, the short position of the equally weighted strategy sells expensive protection against jump risk. Therefore, it yields a positive return from the short position if the swap forward rate does not jump. We find that the number of large jumps is rare, and therefore the short position contributes to an increase in the Sharpe ratio.

Second, we uncover that adopting longer maturity swaption straddles leads to higher values of risk and returns. Consequently, it does not generate a higher Sharpe ratio. Third, the equally weighted strategy is not strongly linked to market state variables, including the implied volatility in the stock market (e.g., Ang et al., 2006), U.S. economic policy uncertainty (Baker et al., 2016), total macro uncertainty (Jurado et al., 2015), monetary policy uncertainty (Husted et al., 2020), and the default spread (e.g., Cooper et al., 2022). Fourth, the profits of the equally weighted strategy are robust, excluding swap rate jumps. This implies that the profitability of our strategy does not concentrate on the interest rate market turmoil triggered by the COVID-19 pandemic period. Fifth, we find that delta hedges in the long position of the straddle reduce the Sharpe ratio. Finally, the equally weighted strategy maintains the profits after including transaction costs. These six results are not observed in the work of DZ (2015). Our equally weighted strategy in the USD interest rate swaption market is a promising approach for U.S. bond investors. This contrasts with the results of DZ (2015), who report that the profitability of the swaption strategies with transaction costs is marginal.

The paper is organized as follows: Section 2 demonstrates related literature, Section 3 describes the methodologies to construct swaption straddles, Section 4 explains our data, Section 5 presents the main empirical results, Section 6 conducts further analysis, and Section 7 concludes.

2. Related literature

This study is associated with volatility risk. Bakshi and Kapadia (2003) investigate volatility risk premiums to construct delta-hedged option portfolios in the equity market. Low and Zhang (2005) apply the same methodology to the OTC currency options market. DZ (2015) focus on the interest rate swaption market and find that the delta-gamma (delta-vega) neutral strategy hedge jump (volatility) risk. The jump risk premium in the stock market is linked to the demand for protection against jump risk (Todorov, 2010) and investors' fear of disasters (Bollerslev and Todorov, 2011).

Our study exploits information of term structures in the options market. The early work of Stein (1989) investigated the term structure in the S&P100 index options market and uncovered that the long maturity options overreacted more than their short-maturity options. The term structure of the Chicago Board Options Exchange (CBOE) Volatility Index (VIX) reflects future returns of variance assets such as S&P500 variance swaps and S&P500 straddles (Johnson, 2017). Recently, the term structure of the variance swap rates in the stock market has received attention (Egloff et al., 2010; Dew-Becker et al., 2017; Aït-Sahalia et al., 2020). Egloff et al. (2010) propose a two-factor model that captures the term structure of the variance swap rates. Dew-Becker et al. (2017) claim that only the transitory component of volatility is priced. Aït-Sahalia et al. (2020) report that investors' demand for protection against volatility risk is stronger for short maturities after a market crash.

Term structures of volatility risks in the interest swap and swaption markets are explored by Trolle and Schwartz (2014), DZ (2015), and Choi et al. (2017). Trolle and Schwartz (2014) and DZ (2015) uncover a downward slope function across maturities in the USD interest rate swaptions. Choi et al. (2017) find the profitability of delta hedged variance swap positions in the U.S. Treasury market. The research of DZ (2015) is strongly related to our study since they adopt a long-short combination of straddles in the swaption market and investigate the term structure. However, we extend various points, as described in Section 1.

Our data cover the unconventional monetary policy period, and this policy is associated with interest rates. Moreover, monetary policy uncertainty impacts interest rates, asset prices, and real economic activities, which are linked to the swap market. Husted et al. (2020) propose the text-based monetary policy uncertainty measure and show that positive uncertainty shocks lead to declines in output. Several studies investigate whether monetary policy uncertainty before and after scheduled Federal Open Market Committee (FOMC) announcements affects the stock market (Lucca and Moench, 2015), the currency market (Mueller et al., 2017), the bond market (Indriawan et al., 2021), and the term structure of the U.S. Treasury market (Brooks et al., 2019). Bretscher et al. (2018) depict that monetary policy uncertainty is connected to interest rate uncertainty, which predicts a slowdown of economic activities. We examine whether the unconventional monetary policy affects the profitability of long-short swaption straddle strategies due to low interest rates and declines in monetary policy uncertainty.

Our two main research questions are as follows:

(i) Does extending maturities of USD interest rate swaptions lead to a high Sharpe ratio?

(ii) Does our equally weighted strategy yield a high Sharpe ratio because of taking exposures to both volatility and jump risks?

3. Methodology

3.1. Pricing of swaption

A European swaption is an option contract that exchanges a fixed interest rate for a floating rate, or vice versa. Investors who buy a payer (receiver) swaption obtain the right to pay the fixed strike price (floating strike price) and receive (pay) the floating price (fixed strike price). The tenor (n) is defined as the period between the exercise date and the date when the last interest payments are exchanged. In contrast, the maturity date (T) refers to the length of time remaining before the exercise date.[5] We employ the Black (1976) model and obtain the straddle price from quoted implied volatility (e.g., Fan et al., 2003; Chaput and Ederington, 2005).

Let $f_t^{(T)}$ be a swap forward rate and follow the geometric Brownian motion:

$$df_t^{(T)} = \sigma f_t^{(T)} dW_t, \quad t < T \tag{1}$$

where σ is constant volatility and W_t is the Brownian motion. Let m be the number of coupon payments per year and N be the principal.[6] Investors who buy the payer swaption exercise the option if the swap forward rate is larger than the strike price f_X at T. Each coupon payment for the payer swaption is

[5] Note that the tenor (n) is expressed in years.

[6] We use $m = 4$ in our empirical analysis.

written as

$$\frac{N}{m}(f_T^{(T)} - f_X)^+. \tag{2}$$

Let $T_1 < \cdots < T_\ell$ be the coupon date for the swaption and $T_0 = T$. The swap begins on the maturity date T of the swaption and ends at time T_ℓ. The time of each coupon payment is denoted as $T_i = T + \frac{i}{m}$ where $1 < i < \ell$ and $\ell = nm$. Following Akume et al. (2003), the option value at time t is obtained as

$$N\frac{e^{-r_t^f T_i}}{m}(f_t^{(T)}\Phi(d_1) - f_X\Phi(d_2)) \tag{3}$$

where r_t^f is the risk-free rate, $\Phi(\cdot)$ is the cumulative normal distribution function, and $d_1,\ d_2$ are written as

$$d_1 = \frac{\log\frac{f_t^{(T)}}{f_X} + \frac{1}{2}\sigma^2 T}{\sigma\sqrt{T}}, \quad d_2 = d_1 - \sigma\sqrt{T}. \tag{4}$$

The total value of the payer swaption $V_t^{P,(T)}$ is calculated as the sum of the option value in Equation (3) and denoted as

$$V_t^{P,(T)} = NA(f_t^{(T)}\Phi(d_1) - f_X\Phi(d_2)) \tag{5}$$

where $A = \sum_{i=1}^{\ell} \frac{e^{-r_t^f T_i}}{m}$.

Investors who buy the receiver swaption exercise the option if the swap forward rate is smaller than the strike price f_X at T. Using Equations (2) to (4), we obtain the total value of the receiver swaption $V_t^{R,(T)}$ as

$$V_t^{R,(T)} = NA(-f_t^{(T)}\Phi(-d_1) + f_X\Phi(-d_2)). \tag{6}$$

In this study, we consider a straddle with the same strike price f_X (Chaput and Ederington, 2005; DZ, 2015). The total value of the straddle $S_t^{(T)}$ is calculated the sum of the total value of the payer and receiver swaptions:

$$S_t^{(T)} = V_t^{P,(T)} + V_t^{R,(T)} = NA\left[f_t^{(T)}(2\Phi(d_1) - 1) - f_X(2\Phi(d_2) - 1)\right]. \tag{7}$$

Equation (7) indicates that the straddle price $S_t^{(T)}$ is the function of the maturity T, the swap forward rate $f_t^{(T)}$, the strike price f_X, the risk-free rate r_t^f and the implied volatility $\sigma_t^{(T)}$, and is written as

$$S_t^{(T)} = S(T, f_t^{(T)}, f_X, r_t^f, \sigma_t^{(T)}) \tag{8}$$

We calculate the total value of the swaption in Equation (8) using the quoted implied Black volatility for the ATM swaption, the risk-free rate, and the swap forward rate (e.g., Trolle and Schwartz, 2014; DZ, 2015). Investors buy (sell) the long (short) position for the ATM swaption straddle and construct the long-short combination of the swaption straddles.

3.2. Returns of straddles

This section describes the methodology for calculating returns of swaption straddles. Let $S_t^{(T)}$ denote the value of a straddle position at time t and we calculate a return $R_t^{(T)}$ as

$$R_t^{(T)} = \frac{1}{N}\left[S(T - \frac{t}{M}, f_t^{(T)}, f_X, r_t^f, \sigma_t^{(T)}) - S(T - \frac{t-1}{M}, f_{t-1}^{(T)}, f_X, r_{t-1}^f, \sigma_{t-1}^{(T)})\right] \tag{9}$$

where M is the number of trading days in a year, and we assume that the maturity T is constant from $t-1$ to t. The first two elements of the value function $S(\cdot)$ are related to the time decay of the option value.

Next, we follow Martellini et al. (2003) and DZ (2015), and describe how to obtain the analytical delta, gamma, and vega using the Black model. Delta $\mathit{\Delta}_t^{(T)}$ is a risk parameter that indicates a change in the price of the underlying swap forward rate, and is obtained by taking the derivative of $S_t^{(T)}$ with respect to $f_t^{(T)}$:

$$\mathit{\Delta}_t^{(T)} = \frac{\partial S_t^{(T)}}{\partial f_t^{(T)}} = NA\left[\Phi(d_1) - \Phi(-d_1)\right]. \tag{10}$$

We follow Bakshi and Kapadia (2003) and employ Equation (10), and the delta-hedged return $R_t^{h,(T)}$ is defined as[7]

$$R_t^{h,(T)} = \frac{1}{N}\left[NR_t^{(T)} - \mathit{\Delta}_{t-1}^{(T)}(f_t^{(T)} - f_{t-1}^{(T)}) - \frac{r_{t-1}^f}{M}(S_{t-1}^{(T)} - \mathit{\Delta}_{t-1}^{(T)} f_{t-1}^{(T)})\right]. \tag{11}$$

Following DZ (2015), the swaption straddle positions are closed in 1 month, and the new positions are initiated in the next month. We focus on the 1-month-holding period because DZ (2015) point out that a longer holding period may lead to difficulties in interpreting the maturity effects on straddle

[7]When we conduct delta-hedges in our empirical analysis, we replace $f_t^{(T)}$ with the spot swap rate $f_t^{(0)}$ and the second term in the right-hand-side in Equation (11) is written as: $\mathit{\Delta}_{t-1}^{(T)}(f_t^{(0)} - f_{t-1}^{(0)})$. This procedure is based on hearing from options trading brokers.

returns.[8] When investors close the swaption straddle position, the value of the position is denoted as: $S\left(T-\frac{1}{12}, f_t^{(T)}, f_X, r_t^f, \sigma_t^{(T-\frac{1}{12})}\right)$. At the same time, investors initiate the new position whose value is $\tilde{S}(T, f_t^{(T)}, r_t^f, \sigma_t^{(T)})$, where $\tilde{S}(\cdot)$ indicates that the strike price of the ATM straddle is $f_t^{(T)}$. Then the rebalanced return $R_t^{r,(T)}$ is calculated as:

$$R_t^{r,(T)} = \frac{1}{N}\left[S\left(T-\frac{1}{12}, f_t^{(T)}, f_X, r_t^f, \sigma_t^{(T-\frac{1}{12})}\right) - \tilde{S}\left(T, f_t^{(T)}, r_t^f, \sigma_t^{(T)}\right)\right]. \tag{12}$$

We consider three strategies for long-short combinations of swaption straddles: equally weighted (*equal*), delta-gamma neutral (*gamma*), and delta-vega neutral (*vega*). Each strategy has a different weight combination of the long and short positions. Let $q_{i,j}$ denote the amount of position. The subscript i indicates the strategies (*equal*, *gamma*, and *vega*) and j indicates the long (L) or short (S) position. Adopting Equations (11) and (12), the total return of the long position $R_{i,L,t}^{(T)}$ is calculated as

$$R_{i,L,t}^{(T)} = \begin{cases} q_{i,L}(R_t^{r,(T)} + R_t^{h,(T)}) & \text{rebalance case} \\ q_{i,L}(R_t^{h,(T)}). & \text{others} \end{cases} \tag{13}$$

Let maturity $T \geq T'$ and the total return of the short position $R_{i,S,t}^{(T')}$ is calculated as

$$R_{i,S,t}^{(T')} = \begin{cases} q_{i,S}(R_t^{r,(T')} + R_t^{h,(T')}) & \text{rebalance case} \\ q_{i,S}(R_t^{h,(T')}). & \text{others} \end{cases} \tag{14}$$

We consider the total return for the equally weighted swaption straddles and define $q_{equal,L} = 1$ and $q_{equal,S} = -1$. Note that the absolute values of the long and short positions are equal in this strategy. When we employ the delta-gamma neutral or delta-vega neutral strategy, the absolute values are different between the long and short positions. Then, we use Equations (13) and (14), and calculate the total return of the long-short positions $LSR_{i,t}$:

$$LSR_{i,t} = (1 + R_{i,L,t}^{(T)})(1 + R_{i,S,t}^{(T')}) - 1, \qquad T' \leq T. \tag{15}$$

[8] Our setting is different from Bakshi and Kapadia (2003) and Low and Zhang (2005), who hold positions until the maturities.

3.3. Hedge positions

This section assesses risk parameters among three strategies and highlights risk exposures of our equally weighted strategy. Moreover, we describe how we determine amounts of the long-short positions for the delta-gamma neutral and delta-vega neutral strategies. To this end, we follow Martellini et al. (2003), Cremers et al. (2015), and DZ (2015), and derive gamma and vega. Gamma $\varGamma_t^{(T)}$ indicates a change of the delta $\varDelta_t^{(T)}$ to the underlying swap forward rate $f_t^{(T)}$. This is obtained by taking the derivative of $\varDelta_t^{(T)}$ in Equation (10) with respect to $f_t^{(T)}$:

$$\varGamma_t^{(T)} = \frac{\partial \varDelta_t^{(T)}}{\partial f_t^{(T)}} = \frac{NA}{f_t^{(T)} \sigma_t^{(T)} \sqrt{T}} \left[\Phi'(d_1) + \Phi'(-d_1) \right]. \tag{16}$$

Vega $\nu_t^{(T)}$ shows an option's sensitivity to implied volatility and is derived by taking the derivative of the straddle price $S_t^{(T)}$ in Equation (8) with respect to implied volatility $\sigma_t^{(T)}$:

$$\nu_t^{(T)} = \frac{\partial S_t^{(T)}}{\partial \sigma_t^{(T)}} = NA f_t^{(T)} \sqrt{T} \left[\Phi'(d_1) + \Phi'(-d_1) \right]. \tag{17}$$

Equation (16) demonstrates that a longer length of the maturity T leads to a smaller value of gamma $\varGamma_t^{(T)}$. In contrast, Equation (17) indicates that a longer length of the maturity T leads to a larger value of vega $\nu_t^{(T)}$. We follow Cremers et al. (2015) and DZ (2015), and construct long-short combinations of swaption straddles with shorter (longer) lengths of maturities T_s (T_l) in the short (long) positions. We can summarize this relation as: $\varGamma_t^{(T_s)} \geq \varGamma_t^{(T_l)}$ and $\nu_t^{(T_s)} \leq \nu_t^{(T_l)}$. Adopting these findings, the risk exposures of the equally weighted strategy indicate that the vega is positive and the gamma is negative. Cremers et al. (2015) and DZ (2015) address that the positive vega indicates that this position takes risk exposures to volatility risk and changes in implied volatility lead to profits. Cremers et al. (2015) and DZ (2015) also present the negative gamma, which means that the short position generates profits from risk exposures to jump risk. Investors are willing to pay for protection against jump risk (Todorov, 2010), and hence the short position receives compensation for providing this protection.

DZ (2015) propose the delta-gamma neutral strategy that is not impacted by jump risk. This strategy is constructed by adjusting the amount of the long position $q_{gamma,L}$. Let the amount of the short position $q_{gamma,S} = -1$ and $T_s \leq T_l$. We employ Equation (16) and obtain $q_{gamma,L}$:

$$q_{gamma,L} = \frac{\sqrt{T_l}\sigma_t^{(T_l)} f_t^{(T_l)}}{\sqrt{T_s}\sigma_t^{(T_s)} f_t^{(T_s)}}. \tag{18}$$

We can confirm that $q_{gamma,L} > 1$, since $T_s \leq T_l$. This suggests that investors increase the amount of the long position and offset the effects of gamma that come from the short position. This delta-gamma neutral strategy has positive exposures to vega since longer maturity straddles have larger vega values in Equation (17). Compared with the equally weighted strategy, the delta-gamma neutral strategy generates more profits from increases in implied volatility.

Similarly, DZ (2015) derive the delta-vega neutral strategy that insulates volatility risk. Let the amount of the short position $q_{vega,S} = -1$ and that of the long position $q_{vega,L}$ is obtained as

$$q_{vega,L} = \frac{\sqrt{T_s} f_t^{(T_s)}}{\sqrt{T_l} f_t^{(T_l)}}. \tag{19}$$

We can see that $q_{vega,L} < 1$, which demonstrates that the delta-vega neutral strategy has negative exposures to gamma since shorter maturity straddles have larger values of gamma in Equation (16). This also leads to larger profits from the short position of jump risk compared with those of the equally weighted strategy.

4. Data

This section describes the data set employed in this study. We focus on the USD interest rate swaption market, which represents the largest swaption market.[9] Moreover, credible data for other countries are not obtained by widely used data providing services. First, we use implied volatilities of ATM forward USD swaptions and obtain daily close prices (Fan et al., 2003; Driessen et al., 2003; DZ, 2015). The data are obtained from Bloomberg, which is based on most trades implemented by investors (DZ, 2015).[10] We also adopt daily close price of swap forward rates from Refinitiv Datastream.[11] For both implied

[9]For instance, the CFTC reports that the gross notional outstanding of the USD interest rate swaption in December 2023 is 13 trillion USD, the euro interest rate swaption is 8 trillion USD, the GBP interest rate swaption is 1.6 trillion USD, and the JPY interest rate swaption is 0.9 trillion USD.

[10]For instance, the ticker code for the 10-year tenor and 1-month maturity is "USSN0A10". We select the data source as BBIR, which covers longer periods and wider ranges of maturities and tenors.

[11]For instance, the RIC code for the 10-year tenor and 1-month maturity is "USDAM3L1MF10Y".

volatilities and swap forward rates, we employ three different swap tenors (5, 10, and 20 years) and six different swap maturities (1, 3, and 6 months; and 1, 5, and 10 years). The data extend from March 31, 2007, to April 30, 2022, which covers around 15 years.[12]. Our starting period differs from that of DZ (2015) because implied volatility data are obtained only from 2007 by Bloomberg. Implied volatility obtained from Bloomberg is quoted as normal volatility, $\sigma_t^{N,(T)}$. We transform normal volatility into Black volatility $\sigma_t^{(T)}$ using the following approximation (e.g., Choi et al., 2022) :

$$\sigma_t^{(T)} \simeq \frac{\sigma_t^{N,(T)}}{f_t^{(T)}}. \tag{20}$$

5. Empirical results

5.1. Black implied volatility

This section reports our empirical results. We begin with summary statistics of Black implied volatility estimated by Equation (20). Table 1 shows mean, median, standard deviation, maximum, and minimum values of implied volatility for different maturities and tenors. We find that the mean value is downward-sloping, which is reported by Trolle and Schwartz (2014) and DZ (2015). Figure 1 also illustrates this downward sloping of implied volatility.

Figure 2 focuses on a 3-month maturity and demonstrates implied volatility for each tenor. We observe that implied volatilities comove across tenors and experience several jumps, which is observed by Fornari (2010) who focuses on a different time period. The jumps correspond to the GFC in 2008, the Taper tantrum triggered by the announcement of future tapering of the FRB's asset purchasing in 2013, the U.S. presidential election in 2016, and the outbreak of COVID-19 in 2020. In particular, the outbreak of COVID-19 has the largest impact, which leads to a larger mean value in Table 1 than that of DZ (2015). For instance, the mean value for the 10-year tenor and the 1-year maturity is 35.9% in this study, while DZ (2015) report a mean value for the same tenor and maturity of 21.6%. This large jump in Black implied volatility is generated by both an increase in normal volatility and a decline in

[12]We extend the data to September 29, 2023 and observe that the tight monetary policy does not impact our conclusion (Table A7)

the swap forward rate in Equation (20). In particular, the decline in the swap forward rate plays an important role during the pandemic. For instance, the swap forward rate during the GFC is around 4%, whereas it goes below 1% during the pandemic period. This is linked to the FRB's expansionary monetary policy (Bernanke, 2020; Bauer et al., 2022).

5.2. Performance of delta-hedged swaption straddles

This section presents the performance of delta-hedged swaption straddles. We follow DZ (2015) and calculate returns and Sharpe ratios for delta-hedged swaption straddles across tenors and maturities. We set $q_{i,L} = 1$ in calculating $R^{(T)}_{i,L,t}$ in Equation (13) and assume that the holding period is 1 month (DZ, 2015).

Table 2 demonstrates means and Sharpe ratios for the returns of swaption straddle long positions. In this table, we observe the mean and the Sharpe ratio for each tenor and maturity. One of the important differences between our work and previous studies, such as DZ (2015) and Choi et al. (2017), is that we include longer maturities such as 5- and 10-years. The 10- and 20-year tenors display negative returns on short maturities, suggesting that investors are willing to pay for protection against volatility risk (e.g., Bakshi and Kapadia, 2003). Aït-Sahalia et al. (2020) address that the demand for protection against volatility risk is stronger for short maturities in the stock market. Our interest rate results also indicate that the demand for protection for longer tenors on shorter maturities is strong. This indicates that selling a swaption straddle position on shorter maturities leads to profits. In contrast, the demand to hedge volatility risk on longer maturities is weak, suggesting that buying a swaption straddle position on longer maturities is relatively inexpensive. Combining these findings, selling shorter maturities and buying longer maturities enhances the performance of the long-short strategy. We will explore this point later.

The straddle returns show upward-sloping for all tenors, which is consistent with the findings of DZ (2015) and Choi et al. (2017). Our new finding is that this upward-sloping is observed in longer maturities such as 5- and 10-years (Figure 3). This upward-sloping for returns is linked to the downward-sloping for implied volatility in Figure 1. Moreover, Figure 1 demonstrates that implied volatility decreases significantly as the maturity exceeds 1-year. Our results are consistent with the results reported by Troll and Schwartz (2014), who present that implied volatility tends to be lower as the maturity lengthens. Our results suggest that adopting longer maturities allows us to enhance the return on the long-short swaption straddle proposed by DZ (2015) because we can access cheaper volatility protection. When we focus on tenors, we find that the returns of longer tenors, such as 10- and 20-years, indicate steeper upward slopes relative to maturity (Table 2 and Figure 3). This finding is associated with the result that implied volatility for longer tenors tends to be small, as demonstrated by Figure 2.

Panel B in Table 2 presents that all Sharpe ratios for the 1-year tenor are negative because the returns are smaller than the risk-free rate, which is calculated based on the 3-month treasury bill rate. Moreover, when we employ maturities of 3- and 6-months, Sharpe ratios for all tenors demonstrate negative values. These results suggest that the long position of the long-short swaption straddle portfolios should adopt long tenors and maturities to achieve a higher Sharpe ratio.

5.3. Long-short strategy

Having found the term structure of volatility risk, we adopt this information and construct long-short positions. We follow Cremers et al. (2015) and DZ (2015), and go long in longer maturity straddles and go short in shorter maturity straddles. We employ 3- and 6- month straddles in the short position and use 1-, 5-, and 10-year straddles in the long position. The important difference from the work of DZ (2015) is that they deploy 3-, 6-, 9-, and 12-month maturities, whereas we employ longer maturities, such as 5 and 10 years. The downward-sloping term structure of implied volatility is steeper in longer maturities, and we exploit this feature. Another important difference is that we employ 5-, 10-, and 20-year tenors, while DZ (2015) use 2- and 10-year tenors.

Table 3 shows the performances of the equally weighted long-short straddles for each tenor. The first column represents the combination of the long-short maturities. For instance, 3M1Y indicates that the maturity of the short position is 3 months and that of the long position is 1 year. Table 3 demonstrates that a longer tenor generates a higher performance for the same maturity combination. For example, the 3M1Y strategy increases the Sharpe ratio from 0.281 to 0.927 as the tenor increases. Adopting a longer maturity straddle in the long position and a shorter maturity straddle in the short position lead to a higher return, which is consistent with the results in Table 2. However, longer and shorter maturity combinations do not generate higher Sharpe ratios due to their high return fluctuations (Figure 4). Consequently, the 3M1Y strategy generates the highest Sharpe ratio for each tenor.

Next, we move onto the performance of the delta-gamma neutral strategy. Table 4 reports the results of the delta-gamma neutral strategy and we observe the same pattern with the equally weighted strategy. A longer tenor generates a higher Sharpe ratio for each maturity combination, and the 3M1Y strategy provides the highest Sharpe ratio for each tenor. DZ (2015) also report that the 3M1Y strategy demonstrates a high Sharpe ratio, while the value is larger than that in this study. For instance, Table 4 demonstrates that the Sharpe ratio of the 3M1Y strategy for the 10-year tenor is 0.42, whereas the corresponding result in DZ (2015) is 0.95. This is due to an increase in Black implied volatility during our sample data including the pandemic period, which leads to an increase in the strategy return fluctuation. Figure 5 also confirms this pattern. Compared with the equally weighted strategy, the delta-gamma neutral strategy shows a higher fluctuation of the cumulative return. Another notable point of the delta-gamma neutral strategy is that the wider maturity gap between the long and short positions leads to an increase in the return fluctuation. This comes from a larger amount of the long position in Equation (18).

Finally, Table 5 presents the results of the delta-vega neutral strategy. We confirm the same pattern with the previous two strategies. The 20-year tenor yileds a higher Sharpe ratio across all maturity combinations, with the 3M1Y strategy producing the highest Sharpe ratio for each tenor. Moreover, we find that the Sharpe ratio of this strategy is the same level of that reported by DZ (2015). Figure 5 illustrates that the delta-vega neutral strategy generates stable returns, except for the GFC and the COVID-19 periods, which suggests that the demand for protection against jump risk is stable.

When we focus on the 10-year tenor and the 3M1Y maturities, we find that the Sharpe ratio for the equally weighted strategies outperforms that of the other two strategies (Tables 3, 4, and 5). The equally weighted strategy takes positive vega and negative gamma, as shown by Equation (17). The delta-gamma neutral strategy takes a greater value of vega than the equally weighted strategy, as in

Equation (18). This suggests that a change in implied volatility leads to a higher return for the delta-gamma neutral strategy (Cremers et al., 2015). However, the monetary easing by the FRB lowers forward swap rates and uncertainty in interest rates, as suggested by Bernanke (2020) and Bauer et al. (2022). This reduces the Sharpe ratio for the delta-gamma neutral strategy. In addition to volatility risk, the equally weighted strategy takes exposures to jump risk (Cremers et al., 2015). If there is no large jump of the forward swap rate, the short position of the equal weight strategy leads to a positive return. This is because the short position indicates selling expensive protection against jump risk (e.g., Aït-Sahalia et al., 2020). Figure 5 demonstrates that the effects of jump risk are not so large in our sample period, suggesting that the unconventional monetary policy reduces the possibility of jumps. Our results indicate that the equally weighted strategy compensates for a decline in volatility risk to take jump risk. Moreover, the comparison between the equally weighted strategy and the delta-vega neutral strategy reveals that solely considering jump risk is insufficient for increasing the Sharpe ratio. Although the effects are smaller than those in DZ (2015), our results indicate that taking volatility risk leads to a higher Sharpe ratio.

In summary, we find that the equally weighted strategy shows a higher performance during our sample period, which encompasses both the market turmoil and tranquil periods. This is related to the positive vega and the negative gamma for the equally weighted strategy.

5.4. Sub-sample analysis

In this section, we conduct a sub-sample analysis and assess the performance of each strategy during different market states. We consider the following three subperiods: November 2008 - October 2014 (Period I), November 2014 - February 2020 (Period II), and March 2020 – March 2022 (Period III). Period I represents the unconventional monetary policy period, during which the FRB conducted the zero interest rate policy and three rounds of large-scale asset purchases (LSAPs). These policies reduced both short-term and long-term interest rates (Figure A4) and swap forward rates (Figure A3). Period II includes a conventional monetary policy period, where the FRB raised the Federal Fund rate from December 2015 and cut it from August 2019. Period III indicates the pandemic period, during which the FRB deployed the zero interest rate policy and LSAPs again to mitigate the negative impacts of the pandemic.

Table 6 demonstrates that the high Sharpe ratio for the equally weighted strategy stems from the delta-vega neutral strategy during Period I. Although the unconventional monetary policies mitigated uncertainty in the market, risk aversion among investors was still high due to the GFC. These active monetary policies also caused low monetary policy uncertainty (Figure A5). This market situation increased demands for protection against jump risk, and hence the delta-vega neutral strategy generated a high Sharpe ratio. This, in turn, led to a high Sharpe ratio for the equally weighted strategy.

We also observe that the equally weighted strategy outperforms the other two strategies in terms of the Sharpe ratio during Period II (Panel B in Table 6). Both the delta-gamma and delta-vega strategies show declines in the Sharpe ratios. The negative return period for the delta-gamma strategy comes from the easing monetary policy between 2018 and 2019.[13] The FRB cut the Federal Fund rate, leading to a decline in market uncertainty. This market situation negatively impacted the return on the delta-gamma strategy. Moreover, the Sharpe ratio of the delta-vega strategy during Period II declined compared with Period I. The demand for protection against jump risk also decreased in this period because the easing monetary policy did not lead to a rapid change in interest rates, in contrast to Period I.

Period III includes the effects of the pandemic and unconventional monetary policies. The relatively lower Sharpe ratio of the equally weighted strategy during Period III is due to the lower performance of the delta-gamma neutral strategy (Panel C in Table 6). The market turmoil in the beginning of the pandemic benefited the delta-gamma neutral strategy, but aggressive monetary easing reduced uncertainty of the market, leading to a decline in the return during Period III. In contrast, the interest rate cut negatively impacted the return on the delta-vega neutral strategy at the start of the pandemic, but the subsequent decline in uncertainty had positive effects on this strategy. This led to a decline in the possibility of jumps.

[13]However, Figure A5 demonstrates that monetary policy uncertainty decreased, and the delta-gamma neutral strategy temporarily generated high returns while the FRB gradually raised the Federal Fund rate.

6. Further analysis

In this section, we conduct further investigation. Section 6.1 focuses on effects of jump risk, Section 6.2 explores whether adopting delta hedges leads to a higher return for the swaption strategies, Section 6.3 estimates our swaption strategies' exposures to risk factors, Section 6.4 adopts a different volatility model, Section 6.5 assesses impacts of transaction costs, and Section 6.6 demonstrates performance in moneyness. To save space, we present only the results of Sections 6.1 and 6.2 in our main manuscript. We display the other results in Online Appendix. We consider the results in Section 6.1 to be important. This is because DZ (2015) report that excluding jump risk generates a higher return for the delta-gamma neutral strategy, but our results do not show this pattern. Moreover, Section 6.2 provides new findings from an investment application perspective since DZ (2015) always assume to adopt delta hedges.

6.1. Effects of jump

This section explores whether jump risk affects the performance of our strategies. Following DZ(2015), we define jump periods using two methodologies. The first method is detecting a jump day when a change in the 10-year spot swap rate return experiences lower than the 0.5% or higher than 99.5% values of the historical returns. We employ a rolling window approach with a window size of past 250 days. The second approach is the methodology proposed by Lee and Mykland (2008), which disentangles jump and high volatility periods. We estimate 1% and 5% values on the 10-year spot swap rate returns to detect jumps.

Table 7 presents the results when we set portfolio returns on jump days to zero. We find that the three strategies are generally robust to jumps since the Sharpe ratios including jumps do not differ from those excluding jumps, except for the result excluding jumps using the rolling-window approach (Panel B in Table 7). DZ (2015) report that jump risk lowers the portfolio returns for the delta-gamma neutral strategy and our rolling window result in Panel B is consistent with their finding. However, the other two results in Panel B do not demonstrate this pattern because volatility on swap forward rates in our sample period is smaller than that in DZ (2015) and the impacts of the jump risk become minor. This finding is also observed in Panel C of Table 7. DZ (2015) display that excluding jumps leads to increases in returns for the delta-vega neutral strategy, whereas our results present that this effect is marginal.

Overall, the jump risk does not significantly impact our three swaption straddles strategies. In particular, we observe that the high Sharpe ratio for the equally weighted strategy excluding the jump periods is robust.[14]

6.2. Effects of delta hedge

This section investigates whether investors should adopt delta hedges in the swaption straddle strategies. Choi et al. (2017) provide empirical evidence that delta hedges contribute to enhance the investment performance in short positions, whereas it is still open whether they function in long positions. DZ (2015) employ delta hedges for all strategies since the delta hedges allow us to mitigate the effects of changes in the swap forward rates and to obtain profits as declines in maturities. We consider another effect provided by delta hedges. Long positions increase the profits as increases in implied volatility since they have the positive vega in Equation (17).

We focus on the 3M10Y combination and calculate the return in the short position with delta hedges and that in the long position without delta hedges. Table 8 reports the performance comparisons. The performances of the long positions with delta hedges are obtained from Tables 2-5. Panel A in Table 8 shows that three out of the four results for the 10-year tenor generate higher Sharpe ratios without delta hedges. In particular, the effects of delta hedges are large for the delta-gamma neutral strategy since it has a large amount of the long position in Equation (18). Panel B in Table 8 reports that all four results for the 20-year tenor have higher Sharpe ratios, which suggest that adopting delta hedges in the long positions does not improve the performance of the long-short straddles. In summary, we observe that adopting delta hedges in the long positions leads to declines in the straddles performances.

[14] The effects of jumps are marginal for the equally weighted strategy against changes in tenors and maturities. See Table A8.

6.3. Risk exposures

This section investigates whether our strategies have exposure to bond factors and state variables that affect swap forward rates. We consider the following regression model:

$$LSR_{i,t} = a + bX_t + e_{i,t} \tag{21}$$

where $LSR_{i,t}$ indicates the return for each strategy, X_t includes bond factors or state variables, a and b are estimated parameters, and $e_{i,t}$ is an error term. We choose the end of month $LSR_{i,t}$ value and run this regression at a monthly frequency. We employ the following bond factors: yields of the 10-year Treasury futures (DZ, 2015), carry (Koijen et al., 2018), momentum (Brooks et al., 2018), level (e.g., Nelson and Siegel, 1987), slope (e.g., Nelson and Siegel, 1987), and implied volatility on the swap forward rate (DZ, 2015). We employ a 7-year zero-coupon Treasury yield as the level factor, and the difference between 10-year and 3-month zero-coupon Treasury yields as the slope factor.

Table A2 presents that the equally weighted strategies have positive exposure to the yields of the Treasury futures and negative exposure to the level factors. Importantly, all results demonstrate that the constant terms are statistically significant at the 5% level, suggesting that the profitability of the equally weighted portfolios is not explained by the bond factors.[15]

We also employ the following market state variables: excess returns on S&P500, VIX (e.g., Ang et al., 2006), TED spread (e.g., Asness et al., 2013), U.S. economic policy uncertainty (Baker et al., 2016), financial uncertainty (Jurado et al., 2015), total macro uncertainty (Jurado et al., 2015), monetary policy uncertainty (Husted et al., 2020), and default spread (BBB; e.g., Cooper et al., 2022). The TED spread is calculated using the 3-month LIBOR and Treasury yields. The default spread is calculated using the Baa corporate and 10-year Treasury yields. Table A3 shows that none of the market state variables significantly impacts the returns on the equally weighted strategy, suggesting that this strategy is robust to changes in market states.

[15]The risk exposure regression results for the delta-gamma neutral and delta-vega neutral strategies are available upon the request.

6.4. SABR model

To check the robustness of our results, we employ a different volatility model. We adopt the SABR model that allows us for interactions between implied volatility and the underlying forward rate (Hagan et al., 2002). Following Bartlett (2006) and Rebonato et al. (2009), we obtain the modified SABR's delta. We replace the delta in Equations (10) and (11) with SABR's delta.[16]

Table A4 presents the equally weighted results using the 10- and 20-year tenors. We observe the differences between Sharpe ratios obtained by the Black model (SR_B) and those calculated by the SABR model (SR_S). We find that our high Sharpe ratios for the equally weighted strategy do not depend on the Black model.

6.5. Transaction costs

This section considers whether the equally weighted strategy maintains profits after taking into account transaction costs. Transaction costs are decomposed into two components: hedge costs (HC) and rebalance costs (RC). The HC_t are calculated as

$$HC_t = phc\frac{\left(\mathit{\Delta}_{t-1}^{(T)} - \mathit{\Delta}_{t-2}^{(T)}\right)}{N} \tag{22}$$

where phc is the proportional cost of the hedge and we assume that 0.5 basis points.[17] When investors buy an ATM straddle position $\tilde{S}(T, f_t^{(T)}, r_t^f, \sigma_t^{(T)})$ and sell a straddle position $S(T-\frac{1}{12}, f_t^{(T)}, f_X, r_t^f, \sigma_t^{(T-\frac{1}{12})})$, and the RC_t is obtained as

$$RC_t = prc\frac{\left[\tilde{S}(T, f_t^{(T)}, r_t^f, \sigma_t^{(T)}) + S(T-\frac{1}{12}, f_t^{(T)}, f_X, r_t^f, \sigma_t^{(T-\frac{1}{12})})\right]}{N} \tag{23}$$

where prc is the proportional cost of rebalance. We estimate the HC at a daily frequency and the RC at a monthly frequency. Figure A1 demonstrates the break-even points of the prc. The x-axis indicates the prc and the y-axis displays the annualized returns on the equally weighted strategy. We calculate the annualized returns including the HC. We observe that the break-even points range from 65 to 75

[16]We provide the details in Online Appendix.
[17]This assumption is based on hearing from broker-dealers.

basis points, which are higher than the results of DZ (2015). These results indicate that our strategy remains the profit after subtracting transaction costs.

In addition, we obtain bid and ask prices on normal volatility using Bloomberg and calculate bid-ask based rebalance costs (RC_{bac}) as

$$RC_{bac,t} = \frac{\left(\tilde{S}(T, f_t^{(T)}, r_t^f, \sigma_{t,bid}^{(T)}) - \tilde{S}(T, f_t^{(T)}, r_t^f, \sigma_{t,ask}^{(T)})\right)}{N} \tag{24}$$

where $\sigma_{t,bid}^{(T)}$ indicates the bid price on normal volatility and $\sigma_{t,ask}^{(T)}$ demonstrates the ask price on normal volatility. Figure A2 confirms a decline in the $RC_{bac,t}$ over time, which supports that the equally weighted strategy generates profits.

Overall, we observe that the equally weighted strategy yields positive profits after including transaction costs.

6.6. Performance in moneyness

This section explores whether our results are robust when we employ out-of-the-money forward USD swaptions. Following Bakshi and Kapadia (2003), we employ implied volatilities of out-of-the-money forward USD swaptions and construct the equally weighted swaption straddle strategy. Table A6 presents that moneyness between -25 and 25 basis points generates the positive profit that comes from the short position. We also find that the long position yields a positive profit when the forward swap rate declines significantly (moneyness between 25 to 100 basis points).

7. Conclusion

This study explores swaption straddle strategies during the low interest rate period. After the GFC, unconventional monetary policies implemented by the FRB led to lower interest rates and a decline in short rate uncertainty (Bernanke, 2020; Bauer et al., 2022). This trend also impacted the swaption market. We extend the work of DZ (2015) and investigate the swaption straddle strategies using longer maturity and tenors, which is related to the findings of Trolle and Schwartz (2014) and Choi et al.

(2017), who report the downward-sloping term structure of implied volatilities in the USD swap and Treasury markets. We propose the equally weighted strategy that takes exposure to volatility and jump risks, which endorse distinct information (Cremers et al., 2015).

We find that Black implied volatility increased significantly during the U.S. presidential election and the COVID-19 pandemic periods. A decline in the swap forward rate was a main driving force during these periods. In contrast, Black implied volatility was relatively stable except for these periods due to the expansionary monetary policies. These market situations caused a decline in the Sharpe ratio of the delta-gamma neutral strategy proposed by DZ (2015). Our equally weighted strategy demonstrates a higher Sharpe ratio than that of the delta-gamma neutral strategy since it takes less exposures to volatility risk.

Moreover, we investigate several methodologies that enhance the swaption straddle strategies. We uncover that investors receive higher profits using the delta hedges only for the short positions in the long-short swaption straddle strategies. We also find that adopting a 20-year tenor causes a higher Sharpe ratio. However, employing longer maturity swaptions leads to increases in both returns and risk, and hence does not generate a higher Sharpe ratio.

Our results demonstrate that the unconventional monetary policy influenced the performance of the USD interest rate swaption strategies. In particular, the return on the delta-gamma neutral strategy declined, suggesting that USD interest rate swaption investors need to employ new investment strategies during this period. This situation may impact investors' activities and the stability of the financial market. The previous literature reports that a monetary easing policy leads to a decline in risk aversion for investors and an increase in bank leverage (Bekaert et al., 2013; Bruno and Shin, 2015). Bekaert et al. (2013) focus on stock market risk aversion, but our results imply that bond investors may also construct riskier portfolios to compensate for the loss of strategies. Policymakers consider these changes in investors' behavior to monitor financial market stability.

Table 1: Summary statistics of Black implied volatility

Panel A: Maturity					
	Mean	St.Dev	Med	Min	Max
1M	38.88	19.69	35.80	9.730	280.4
3M	38.43	18.53	35.44	10.70	218.3
6M	37.53	16.58	34.66	11.01	166.8
1Y	35.92	14.84	33.56	11.60	145.8
5Y	28.76	10.00	27.13	12.39	98.48
10Y	24.92	9.064	23.66	11.21	80.98
Panel B: Tenor					
	Mean	St.Dev	Med	Min	Max
5Y	47.19	21.75	46.00	11.90	234.1
10Y	38.43	18.53	35.44	10.70	218.3
20Y	33.41	16.74	30.10	9.684	200.2

Notes: This table reports means, standard deviations (St.Dev), median (Med), minimum (Min) and maximum (Max) values of annualized swaption implied volatility. The implied volatility is estimated based on Black (1976) and Equation (20). Panel A presents the results for each maturity and we employ a 10-year tenor. Panel B demonstrates the results for each tenor and we adopt a 3-month maturity. All values are measured in percentage points (%). The sample period extends from March 31, 2007 to April 30, 2022.

Table 2: Returns and Sharpe ratios for long positions of delta-hedged swaption straddles

Panel A: Return(%)

	Maturity				
	3M	6M	1Y	5Y	10Y
Tenor					
1Y	0.25	0.25	0.23	0.30	0.34
5Y	0.14	0.34	0.99	1.16	1.37
10Y	-0.93	-0.15	1.81	2.23	2.70
20Y	-3.26	-1.43	1.44	4.65	5.51

Panel B: Sharpe ratio

	Maturity				
	3M	6M	1Y	5Y	10Y
Tenor					
1Y	-0.78	-0.77	-0.80	-0.42	-0.29
5Y	-0.29	-0.18	0.12	0.13	0.16
10Y	-0.40	-0.21	0.23	0.20	0.25
20Y	-0.52	-0.29	0.09	0.32	0.34

Notes: This table presents annualized returns and Sharpe ratios for long positions using Equation (13). We assume that investors rebalance delta hedged swaption straddle positions at a monthly frequency.

Table 3: Returns and Sharpe ratios for the equally weighted long-short swaption straddle strategy

	Return(%)	St.Dev(%)	SR
Panel A: 5-year tenor			
3M1Y	1.324	2.171	0.281
3M5Y	1.574	3.531	0.243
3M10Y	1.782	4.026	0.265
6M1Y	0.971	2.335	0.110
6M5Y	1.220	3.543	0.143
6M10Y	1.428	4.070	0.175
Panel B: 10-year tenor			
3M1Y	3.179	3.264	0.755
3M5Y	4.455	6.689	0.559
3M10Y	4.932	7.756	0.544
6M1Y	1.830	2.772	0.402
6M5Y	3.090	6.287	0.378
6M10Y	3.560	7.304	0.390
Panel C: 20-year tenor			
3M1Y	6.302	6.028	0.927
3M5Y	9.668	10.14	0.883
3M10Y	10.57	13.08	0.753
6M1Y	3.253	4.909	0.517
6M5Y	6.522	8.904	0.652
6M10Y	7.395	12.00	0.557

Notes: This table presents annualized returns, standard deviations and Sharpe ratios for the equally weighted long-short swaption straddle strategy using Equation (15). We assume that investors rebalance the delta hedged swaption straddle position each month. The first two letters in the first column indicate maturity in the short position and the latter two letters display that in the long position. We employ 5-, 10-, 20-year tenors. The weight of the long position is obtained as: $q_{equal,L} = 1$ and that of the short position is written as: $q_{equal,S} = -1$.

Table 4: Returns and Sharpe ratios for the delta-gamma neutral long-short swaption straddle strategy

	Return(%)	St.Dev(%)	SR
Panel A: 5-year tenor			
3M1Y	1.796	4.206	0.257
3M5Y	2.363	17.79	0.093
3M10Y	2.005	28.45	0.045
6M1Y	1.200	2.960	0.164
6M5Y	2.125	12.12	0.116
6M10Y	2.597	19.38	0.097
Panel B: 10-year tenor			
3M1Y	3.299	6.171	0.419
3M5Y	5.595	31.13	0.157
3M10Y	5.004	48.34	0.089
6M1Y	1.956	3.862	0.321
6M5Y	4.782	21.79	0.187
6M10Y	5.522	33.75	0.142
Panel C: 20-year tenor			
3M1Y	5.826	10.57	0.484
3M5Y	12.47	43.74	0.269
3M10Y	8.504	70.53	0.110
6M1Y	3.231	6.463	0.389
6M5Y	10.67	29.68	0.335
6M10Y	11.88	48.77	0.229

Notes: This table presents annualized returns, standard deviations and Sharpe ratios for the delta-gamma neutral long-short swaption straddle strategy using Equation (15). We assume that investors rebalance the delta hedged swaption straddle position each month. The first two letters in the first column indicate maturity in the short position and the latter two letters display that in the long position. We employ 5-, 10-, 20-year tenors. The weight of the long position $q_{gamma,L}$ is obtained by Equation (18) and that of the short position is written as: $q_{gamma,S} = -1$.

Table 5: Returns and Sharpe ratios for the delta-vega neutral long-short swaption straddle strategy

	Return(%)	St.Dev(%)	SR
Panel A: 5-year tenor			
3M1Y	0.882	1.695	0.098
3M5Y	0.622	2.031	-0.046
3M10Y	0.607	2.047	-0.053
6M1Y	0.711	1.926	-0.002
6M5Y	0.358	2.079	-0.172
6M10Y	0.339	2.080	-0.181
Panel B: 10-year tenor			
3M1Y	2.751	3.120	0.653
3M5Y	2.710	3.839	0.520
3M10Y	2.675	4.098	0.478
6M1Y	1.600	2.609	0.339
6M5Y	1.577	3.648	0.236
6M10Y	1.532	3.938	0.208
Panel C: 20-year tenor			
3M1Y	5.697	6.036	0.825
3M5Y	5.997	7.269	0.727
3M10Y	5.931	7.719	0.676
6M1Y	2.948	4.757	0.469
6M5Y	3.423	6.331	0.428
6M10Y	3.339	7.023	0.374

Notes: This table presents annualized returns, standard deviations and Sharpe ratios for the delta-vega neutral long-short swaption straddle strategy using Equation (15). We assume that investors rebalance the delta hedged swaption straddle position each month. The first two letters in the first column indicate maturity in the short position and the latter two letters display that in the long position. We employ 5-, 10-, 20-year tenors. The weight of the long position $q_{vega,L}$ is obtained by Equation (19) and that of the short position is written as: $q_{vega,S} = -1$.

Table 6: Sub-sample results for three strategies

	Return(%)	St.Dev(%)	SR
Panel A: Period I (2008/11-2014/10)			
Equal Weight	4.459	3.357	1.302
Delta-Gamma Neurtal	3.797	5.616	0.660
Delta-Vega Neurtal	4.229	3.647	1.135
Panel B: Period II (2014/10-2020/3)			
Equal Weight	2.121	2.442	0.431
Delta-Gamma Neurtal	2.326	5.187	0.242
Delta-Vega Neurtal	1.739	2.191	0.306
Panel C: Period III (2020/3-2022/3)			
Equal Weight	1.124	3.810	0.265
Delta-Gamma Neurtal	0.392	8.310	0.033
Delta-Vega Neurtal	1.303	3.294	0.361

Notes: This table presents annualized returns, standard deviations and Sharpe ratios for each long-short swaption straddle strategy using Equation (15). We employ the following three periods: Period I (2008/11-2014/10), Period II (2014/10-2020/3), and Period III (2020/3-2022/3). We assume that investors rebalance the delta hedged swaption straddle position each month. We employ a 10-year tenor with the swaption maturities of the short position being 3 months and those of the long position being one year. For the equally weighted strategy, the weight of the long position is obtained as: $q_{equal,L} = 1$ and that of the short position is written as: $q_{equal,S} = -1$. For the delta-gamma neutral strategy, the weight of the long position $q_{gamma,L}$ is obtained by Equation (18) and that of the short position is written as: $q_{gamma,S} = -1$. The weight of the long position $q_{vega,L}$ is obtained by Equation (19) and that of the short position is written as: $q_{vega,S} = -1$.

Table 7: Performances of three strategies excluding jump effects

	Return(%)	Annual (%)	St.Dev(%)	SR
Panel A: Equally weighted				
Incl. jumps	63.24	3.179	3.264	0.755
Excl. jumps (Rolling window, 1%)	52.18	2.718	3.076	0.651
Excl. jumps (LM2008, 1%)	63.18	3.176	3.245	0.759
Excl. jumps (LM2008, 5%)	62.77	3.160	3.244	0.754
Panel B: Delta-gamma neutral				
Incl. jumps	66.23	3.299	6.171	0.419
Excl. jumps (Rolling window, 1%)	34.07	1.890	5.819	0.202
Excl. jumps (LM2008, 1%)	67.35	3.343	6.150	0.427
Excl. jumps (LM2008, 5%)	66.91	3.325	6.147	0.425
Panel C: Delta-vega neutral				
Incl. jumps	52.96	2.751	3.120	0.653
Excl. jumps (Rolling window, 1%)	55.25	2.849	2.901	0.736
Excl. jumps (LM2008, 1%)	52.44	2.729	3.104	0.649
Excl. jumps (LM2008, 5%)	52.05	2.712	3.103	0.643

Notes: This table presents the effects of jumps. We report daily returns, annualized returns (Annual), standard deviations (St. Dev) and Sharpe ratios (SR) for equally weighted, delta-gamma neutral, and delta-vega neutral strategies. For each strategy, we demonstrate the four results. Base results ("Incl. jumps"), which are reported in Tables 3, 4, and 5. Results of "Excl. jumps (Rolling window, 1%)" indicate that the results of excluding jump periods detected as changes in daily returns on the spot swap rate are lower than the 0.5th percentile or higher than the 99.5th percentile of the past 1-year values. Results of "Excl. jumps (LM2008, 1%)" and "Excl. jumps (LM2008, 5%)" indicate that the results of excluding jump periods detected by Lee and Mykland (2008) and the cutoff rates are 1% and 5%, respectively. We employ a 10-year tenor with the swaption maturities of the short position being 3 months and those of the long position being one year. We use daily data and the sample period extends from March 31, 2007, to April 30, 2022.

Table 8: Comparison between delta-hedged and non delta-hedged strategies

	Return(%)	St.Dev(%)	SR
Panel A: 10-year tenor			
Without delta hedge			
Long	2.766	7.742	0.265
Equally weighted	5.004	7.529	0.570
Gamma neutral	6.553	46.68	0.125
Vega neutral	2.656	4.096	0.474
With delta hedge			
Long	2.696	7.998	0.248
Equally weighted	4.932	7.756	0.544
Gamma neutral	5.004	48.34	0.089
Vega neutral	2.675	4.098	0.478
Panel B: 20-year tenor			
Without delta hedge			
Long	5.926	13.51	0.386
Equally weighted	11.00	12.21	0.842
Gamma neutral	13.03	65.75	0.187
Vega neutral	5.955	7.676	0.683
With delta hedge			
Long	5.511	14.27	0.336
Equally weighted	10.57	13.08	0.753
Gamma neutral	8.504	70.53	0.110
Vega neutral	5.931	7.719	0.676

Notes: This table shows differences between delta-hedged and non delta-hedged swaption straddle strategies. For each tenor, we report annualized returns, standard deviations and Sharpe ratios for long, equally weighted, delta-gamma neutral, and delta-vega neutral strategies. Returns for the long strategy are obtained by Equation (13) and those for the other three strategies are calculated by Equation (15). The weight of the equally weighted long position is obtained as: $q_{equal,L} = 1$ and that of the short position is written as: $q_{equal,S} = -1$. The weight of the delta-gamma neutral long position $q_{gamma,L}$ is obtained by Equation (18) and that of the short position is written as: $q_{gamma,S} = -1$. The weight of the delta-vega neutral long position $q_{vega,L}$ is obtained by Equation (19) and that of the short position is written as: $q_{vega,S} = -1$. The swaption maturities of the short position are 3 months and those of the long position are 10 years.

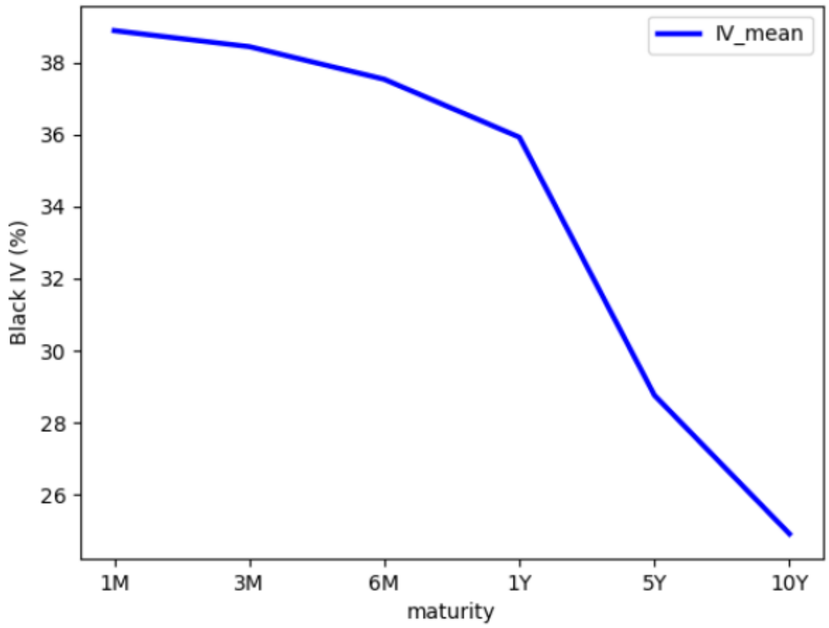

Figure 1. Term structure of Black implied volatility

Notes: This figure displays the term structure of Black (1976) implied volatility, which is estimated by Equation (20). We focus on a 10-year tenor.

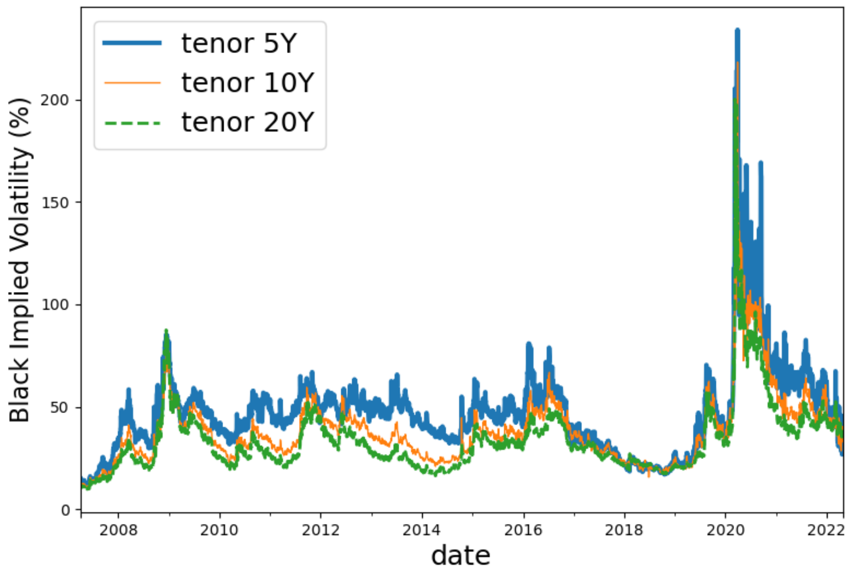

Figure 2. Black implied volatility for each tenor

Notes: This figure displays Black (1976) implied volatility, which is estimated by Equation (20). We focus on 3-month maturity and employ 5-, 10-, and 20-year tenors.

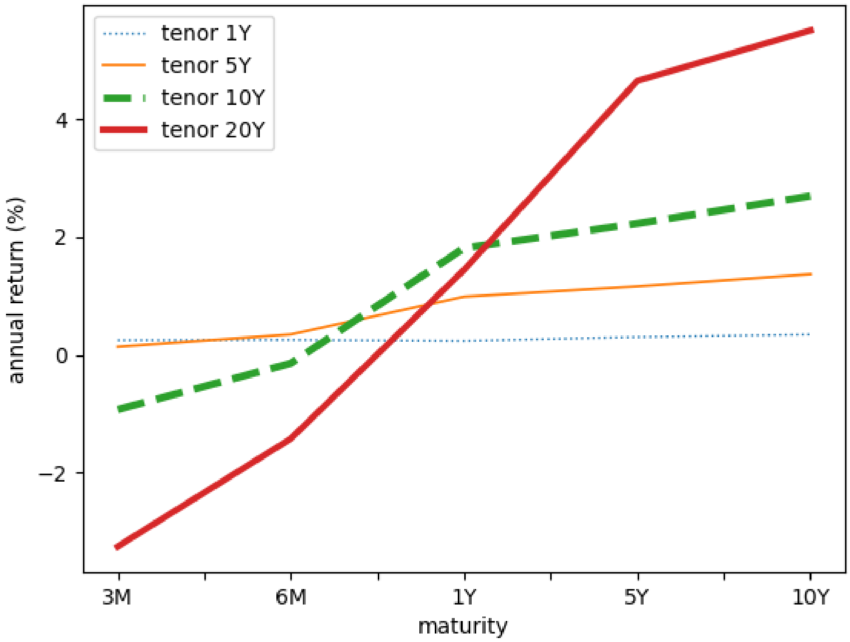

Figure 3. Annualized returns for long positions of delta-hedged swaption straddles using different tenors

Notes: This figure displays annualized returns for long positions using Equation (13). The x-axis indicates maturities. We employ 1-, 5-, 10-, and 20-year tenors.

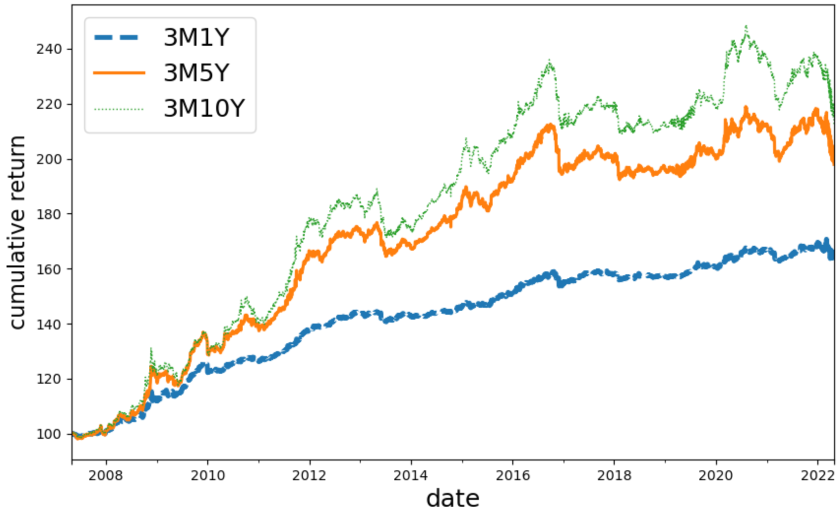

Figure 4. Cumulative returns for the equally weighted long-short swaption straddle strategy of different maturities

Notes: This figure displays cumulative returns for the equally weighted strategy. We employ a 10-year tenor and a 1-month holding period. We use the following combinations of maturities: 3-month (short) and 1-year (long), 3-month (short) and 5-year (long), and 3-month (short) and 10-year (long).

Figure 5. Cumulative returns for three strategies using the same maturities and the tenor

Notes: This figure displays cumulative returns for equally weighted, delta-gamma neutral, and delta-vega neutral strategies. We employ a 10-year tenor and a 1-month holding period. The swaption maturities of the short position are 3 months and those of the long position are 1 year.

Data Availability Statement

(a) Yields of the 10-year Treasury futures, forward and spot rates of 10-year Treasury yields, implied volatility on the swap forward rate, implied volatilities of ATM forward USD swaptions are obtained from Bloomberg.

(b) Zero-coupon Treasury yields and the SP500 index are obtained from Datastream.

(c) The default and TED spreads, U.S. 3-month and 10-year Treasury yields are openly available from the FRED (Federal Reserve Economic Data) service, maintained by the Federal Reserve Bank of St. Louis at: `https://fred.stlouisfed.org/`.

(d) The total macro uncertainty, financial uncertainty, monetary policy uncertainty, and U.S. economic policy uncertainty indices are kindly made available by authors' websites at:
`https://www.sydneyludvigson.com/macro-and-financial-uncertainty-indexes` and
`https://www.policyuncertainty.com/`.

(e) VIX is openly available from the Chicago Board Options Exchange (CBOE).

References

Aït-Sahalia, Y., Karaman, M., and Mancini, L. (2020). The term structure of equity and variance risk premia. *Journal of Econometrics*, 219, 204-230.

Akume, D., Luderer, B., and Weber, G-W. (2003). Pricing and hedging of swaptions. *Journal of Computational Technologies*, 8(4), 5-14.

Ang, A., Hodrick, R.J., Xing, Y., and Zhang, X. (2006). The cross-section of volatility and expected returns. *Journal of Finance*, 61, 259-299.

Asness, C.S., Moskowitz, T.J., and Pedersen, L.H. (2013). Value and momentum everywhere. *Journal of Finance*, 68, 929–985.

Baker, S.R., Bloom, N., and Davis, S.J. (2016). Measuring economic policy uncertainty. *Quarterly Journal of Economics*, 131, 1593-1636.

Bakshi, G. and Kapadia, N. (2003). Delta-Hedged gains and the negative market volatility risk premium. *Review of Financial Studies*, 16, 527-66.

Bakshi, G. and Madan, D. (2006). A theory of volatility spreads. *Management Science*, 52, 1945-56.

Bartlett, B., 2006. Hedging under SABR model. *Witmott Magazine*, 24, 2–4.

Bauer, M.D, Lakdawala, A., and Mueller, P. (2022). Market-based monetary policy uncertainty. *Economic Journal*, 132, 1290–1308.

Bekaert, G., Hoerova, M., and Marco, L.D. (2013). Risk, uncertainty and monetary policy. *Journal of Monetary Economics*, 60. 771-788.

Bekaert, G. and Hoerova, M. (2014). The VIX, the variance premium and stock market volatility. *Journal of Econometrics*, 183.181-192.

Bernanke, B.S. (2020). The new tools of monetary policy. *American Economic Review*, 110, 943-83.

Black, F. (1976). The pricing of commodity contracts. *Journal of Financial Economics*, 3, 167–179.

Bollerslev, T. and Todorov, V. (2011). Tails, Fears and Risk Premia. *Journal of Finance*, 66, 2165-2211.

Bretscher, L., Schmid, L., and Vedolin, A. (2018). Interest rate risk management in uncertain times. *Review of Financial Studies*, 31, 3019-3060.

Brooks, J., Katz, M., and Lustig, H. (2019). Post-FOMC announcement drift in U.S. bond markets. Stanford University Graduate School of Business Research Paper No. 18-2.

Brooks, J., Palhares, D., and Richardson, S. (2018). Style Investing in Fixed Income. *Journal of Portfolio Management*, 127-139.

Bruno, V. and Shin, H.S. (2015). Capital flows and the risk-taking channel of monetary policy. *Journal of Monetary Economics*, 71, 119-132.

Byun, S.J. and Chang, K.C. (2015). Volatility risk premium in the interest rate market: Evidence from delta-hedged gains on USD interest rate swaps, *International Review of Financial Analysis*, 40, 88-102,

Chaput, S. and Ederington, L. (2005). Volatility trade design. *Journal of Futures Markets*, 25, 243–279.

Chang, H-L., Chang, Y-C., Cheng, H-W., Peng, P-H., and Tseng, K. (2019). Jump variance risk: Evidence from option valuation and stock returns. *Journal of Futures Markets*. 39, 890– 915.

Choi, H., Mueller, P., and Vedolin, A. (2017). Bond variance risk premiums. *Review of Finance*, 21, 987-1022.

Choi, J., Kwak, M., Tee, C.W., and Wang, Y. (2022). A Black-Scholes user's guide to the Bachelier model. *Journal of Futures Markets*, 42, 959-980.

Cooper, I., Mitrache, A., and Priestley, R. (2022). A global macroeconomic risk model for value, momentum, and other asset classes. *Journal of Financial and Quantitative Analysis*, 57, 1-30.

Cremers, M., Halling, M., and Weinbaum, D. (2015). Aggregate jump and volatility risk in the cross-section of stock returns. *Journal of Finance*, 70, 577-614.

Dew-Becker, I., Giglio, S., Le, A., and Rodriguez, M. (2017). The price of variance risk. *Journal of Financial Economics*, 123, 225-250.

Drechsler, I. and Yaron, A. (2011). What's vol got to do with it. *Review of Financial Studies*, 24,1-45.

Driessen, J., Klaassen, P., and Melenberg, B. (2003). The performance of multi-factor terms structure models for pricing and hedging caps and swaptions. *Journal of Financial and Quantitative Analysis*, 38, 635-672.

Duyvesteyn, J. and de Zwart, G. (2015). Riding the swaption curve, *Journal of Banking & Finance*, 59, 57-75.

Egloff, D., Leippold, M., and Wu, L. (2010) The term structure of variance swap rates and optimal variance swap investments. *Journal of Financial and Quantitative Analysis*, 45, 1279-1310.

Fang., R., Gupta, A., and Ritchken, P. (2003). Hedging in the possible presence of unspanned stochastic volatility: Evidence from swaption markets. *Journal of Finance*, 58, 2219-2248.

Fornari, F. (2010). Assessing the compensation for volatility risk implicit in interest rate derivatives. *Journal of Empirical Finance*, 17, 722–743.

Hagan, P., Kumar, D., Lesniewski, A., and Woodward, D. (2002). Managing smile risk. *Witmott Magazine*, 1, 84-108.

Husted, L., Rogers, J., and Sun, B. (2020). Monetary policy uncertainty. *Journal of Monetary Economics*, 115, 20-36.

Indriawan, I., Jiao, F., and Tse, Y. (2021). The FOMC announcement returns on long-term US and German bond futures. *Journal of Banking & Finance*, 123, 106027.

Jermann, U.J. (2020). Negative swap spreads and limited arbitrage. *Review of Financial Studies*, 33, 212-238.

Johnson, T.L. (2017). Risk premia and the VIX term structure. *Journal of Financial and Quantitative Analysis*, 52, 2461-2490.

Jurado, K., and Ludvigson, S.C., and Ng, S., (2015). Measuring uncertainty. *American Economic Review*, 105, 1177-1216.

Koijen, R.S.J., Moskowitz, T.J., Pedersen, L., and Vrugt, E.B. (2018). Carry. *Journal of Financial Economics*, 127, 197-225.

Ledoit, O. and Wolf, M. (2008). Robust performance hypothesis testing with the Sharpe ratio. *Journal of Empirical Finance*, 15, 850-859.

Lee, S.S. and Mykland, P.A. (2008). Jumps in financial markets: a new nonparametric test and jump dynamics. *Review of Financial Studies*, 21, 2536–2563.

Low, B.S. and Zhang, S. (2005). The volatility premium embedded in currency options. *Journal of Financial and Quantitative Analysis*, 40, 803-832.

Lucca, D.O. and Moench, E. (2015). The pre-FOMC announcement drift. *Journal of Finance*, 70, 329–371.

Martellini, L., Priaulet, P., and Priaulet, S., (2003). *Fixed income securities: Valuation, risk management and portfolio Strategies*. John Wiley & Sons Ltd., Chichester (West Sussex).

Mele, A. and Obayashi, Y. (2013). Volatility indexes and contracts for government bonds and time deposits. Swiss Finance Institute Research Paper Series, 13-26, Swiss Finance Institute.

Mele, A., Obayashi, Y., and Shalen, C. (2015). Rate fears gauges and the dynamics of fixed income and equity volatilities. *Journal of Banking & Finance*, 52, 256-265.

Mueller, P., Tahbaz-Salehi, A., and Vedolin, A. (2017). Exchange rates and monetary policy uncertainty. *Journal of Finance*, 72, 1213-1252.

Nelson, C. R. and Siegel, A. F. (1987). Parsimonious modeling of yield curves. *Journal of Business*, 60, 473-489.

Newey, W. and West, K. (1987). A simple, positive semi-definite, heteroskedasticity and autocorrelation consistent covariance matrix. *Econometrica*, 55, 703-708.

Rebonato, R., McKay, K., and White, R. (2009). *The SABR/LIBOR market model: pricing, calibration and hedging for complex interest-rate derivatives*, John Wiley & Sons Ltd., Chichester (West Sussex).

Stein, J. (1989). Overreactions in the options market. *Journal of Finance*, 44, 1011-1023.

Todorov, V. (2010). Variance risk premia dynamics: The role of jumps. *Review of Financial Studies*, 23, 345-383.

Trolle, A.B. and Schwartz, E.S. (2014) The swaption cube. *Review of Financial Studies*, 27, 2307-2353.

Data Citations

Baker, S.R., Bloom, N., and Davis, S.J. (2016). Economic policy uncertainty index. https://www.policyuncertainty.com/.

Bloomberg, (2023). Yields of the 10-year Treasury futures, forward and spot rates of 10-year Treasury yields, implied volatility on the swap forward rate, and implied volatilities of ATM forward USD swaptions.

Datastream. (2023). Zero-coupon Treasury yields and the SP500 index.

Chicago Board Options Exchange (CBOE). (2023). VIX.

Federal Reserve Economic Data (FRED). (2023). The default and TED spreads and U.S. 3-month and 10-year Treasury yields. https://fred.stlouisfed.org/series.

Husted, L., Rogers, J., and Sun, B. (2020). Monetary policy uncertainty. https://www.policyuncertainty.com/.

Jurado, K., and Ludvigson, S.C., and Ng, S., (2015). Total macro uncertainty index. https://www.sydneyludvigson.com/macro-and-financial-uncertainty-indexes.

USD interest rate swaption strategies during the unconventional monetary policy and pandemic eras

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A. SABR model

Hagan et al. (2002) propose the SABR model that is described as the following system of stochastic differential equations:

$$\begin{aligned} df_t &= \alpha_t f_t^{\beta} dW_t^1 \\ d\alpha_t &= v \alpha_t dW_t^2 \end{aligned}$$

where f_t is the swap forward rate, α_t is the parameter of volatility, β and v indicate constant parameters. The swap forward rate and volatility is correlated as

$$E[dW_t^1 dW_t^2] = \rho dt$$

where ρ is the correlation coefficient. Following Bartlett (2006) and Rebonato et al. (2009), the modified SABR's delta is obtained as

$$\varDelta_{SABR} = \varDelta + \nu \left[\frac{\partial \sigma}{\partial f} + \frac{\partial \sigma}{\partial \alpha} \frac{\rho \upsilon}{f^{\beta}} \right]$$

where Δ and ν are obtained by the Black model in Equations (10) and (17). We set $\beta = 0.5$, $\sigma = 0.03$, $\rho = -0.25$, and $\upsilon = 0.4$, see, for instance, DZ (2015).

Table A1: Differences of Sharpe ratios

	ΔSharpe	p-value	block size
(a) Equally weighted vs Delta-gamma neutral	0.34	0.04	10
(b) Equally weighted vs Delta-vega neutral	0.10	0.59	10

Notes: This table presents the difference of Sharpe ratio (ΔSharpe) between strategies. Row (a) calculates the difference between the equally weighted and delta-gamma neutral strategies and row (b) estimates that between the equally weighted and delta-vega neutral strategies. The positive values indicate the Sharpe ratio of the equally weighted strategy is higher than that of the other strategies. The p-value of ΔSharpe is computed by Ledoit and Wolf (2008). We employ a 10-year tenor with the swaption maturities of the short position being 3 months and those of the long position being 1 year. We use daily data and the sample period extends from March 31, 2007, to April 30, 2022.

Table A2: Regression results: Equally weighted strategy and bond factors

	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)
a	0.002**	0.003**	0.003**	0.003**	0.003**	0.003**	0.003**	0.002**	0.003**
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
TY	0.282**						0.330*	0.299**	
	(0.062)						(0.158)	(0.053)	
carry		0.008					0.433**	0.241	
		(0.187)					(0.147)	(0.191)	
mom			0.066				-0.135**		
			(0.056)				(0.048)		
level				-0.018**			-0.001		-0.020**
				(0.003)			(0.011)		(0.004)
slope					-0.011**		-0.005		0.001
					(0.004)		(0.004)		(0.004)
vol						0.010	-0.004		-0.005
						(0.005)	(0.003)		(0.004)
adj-R^2	0.327	-0.006	0.012	0.332	0.125	0.018	0.400	0.344	0.330

Notes: This table presents the results that returns on the equally weighted strategy onto the following variables: yields of the 10-year Treasury futures (TY), carry (Koijen et al., 2018), momentum (Brooks et al., 2018), level, slope, and implied volatility on swaption (vol). We employ 7-year zero-coupon Treasury yields as the level factor. The slope factor is calculated as the difference between 10-year and 3-month zero-coupon Treasury yields. We employ a 10-year tenor with the swaption maturities of the short position being 3 months and those of the long position being one year. The standard errors are reported in parentheses and obtained by the Newey and West (1987) procedure. *,**, and *** indicate significance at the 10%, 5% and 1% levels, respectively.

Table A3: Regression results: Equal-weighted strategy and market state variables

	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)
a	0.003**	0.003**	0.003**	0.003**	0.003**	0.003**	0.003**	0.003**	0.003**
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
SP	-0.035								-0.036
	(0.018)								(0.028)
VIX		0.002							-0.005
		(0.002)							(0.003)
TED			-0.000						-0.002**
			(0.001)						(0.001)
Policy				0.003					-0.001
				(0.003)					(0.004)
Fin					-0.010				-0.035
					(0.017)				(0.018)
Macro						-0.006			-0.012
						(0.018)			(0.020)
Money							0.001		0.000
							(0.001)		(0.001)
BBB								0.022*	0.035**
								(0.009)	(0.012)
adj-R^2	0.034	-0.002	-0.004	-0.005	-0.003	-0.005	-0.003	0.062	0.118

Notes: This table presents the results that returns on the equal-weighted strategy onto the following variables: excess returns on SP500 (SP), VIX, TED spread (TED), U.S. economic policy uncertainty (Policy; Baker et al. 2016), financial uncertainty (Fin; Jurado et al., 2015), total macro uncertainty (Macro; Jurado et al., 2015), monetary policy uncertainty (Money; Husted et al., 2020), and default spread (BBB). The TED spread is calculated by the three-month LIBOR and Treasury yields (e.g., Asness et al., 2013). The the default spread is calculated by the Baa corporate and 10-year Treasury yields (e.g., Cooper et al., 2022). We employ a 10-year tenor with the swaption maturities of the short position being 3 months and those of the long position being 1 year. The standard errors are reported in parentheses and obtained by the Newey and West (1987) procedure. *,**, and *** indicate significance at the 10%, 5% and 1% levels, respectively.

Table A4: SABR delta hedged equally weighted strategy

	Return(%)	St.Dev(%)	SR_S	SR_B
Panel A: 10-year tenor				
3M1Y	2.841	3.122	0.681	0.755
3M5Y	3.964	6.484	0.501	0.559
3M10Y	4.343	7.700	0.471	0.544
Panel B: 20-year tenor				
3M1Y	5.681	5.775	0.860	0.927
3M5Y	8.752	9.587	0.838	0.883
3M10Y	9.588	12.22	0.726	0.753

Notes: This table presents annualized returns, standard deviations and Sharpe ratios obtained by the SABR model (SR_S) for equally weighted long-short swaption straddle strategies using Equation (15). We assume that investors rebalance the delta hedged swaption straddle position each month. The first two letters in the first column indicate a maturity in the short position and the latter two letters display that in the long position. We employ 10- and 20-year tenors. The weight of the long position is obtained as: $q_{equal,L} = 1$ and that of the short position is written as: $q_{equal,S} = -1$. We also report Sharpe ratios obtained by the Black model (SR_B). These values are also reported in Table 3.

Table A5: Effects of hedge costs

Annualized return(%)	Without delta-hedge	Delta-hedge	
Maturity			Diff
1Y	0.98	0.44	0.53
10Y	2.77	2.52	0.25

Notes: This table presents annualized returns, Sharpe ratios for long positions using Equation (13), and the difference of the Sharpe ratios. We estimate the results with and without delta hedges. We calculate the costs of delta hedges using Equation (22). We employ a 10-year tenor and the swaption maturities of the long position are 1- and 10-years. The sample period extends from April 30, 2007, to April 30, 2022.

Table A6: Moneyness and annualized returns

Panel A: 3M1Y				
Moneyness (bp)	N	Short	Long	EW
-100 to -50	20	-0.47	-0.12	-0.58
-50 to -25	141	-0.31	-0.65	-0.95
-25 to 25	1954	5.34	-2.80	2.39
25 to 50	87	-1.71	1.96	0.22
50 to 100	10	-0.57	1.11	0.53
Panel B: 3M10Y				
Moneyness (bp)	N	Short	Long	EW
-100 to -50	13	-0.47	-0.40	-0.87
-50 to -25	144	-0.31	-2.72	-3.01
-25 to 25	1949	5.34	-1.39	3.88
25 to 50	92	-1.71	3.85	2.08
50 to 100	14	-0.57	1.21	0.63

Notes: This table presents relationships between annualized returns (%) and moneyness. We employ implied volatilities of out-of-the-money forward USD swaptions and a 10-year tenor. The first column indicates moneyness (bp), where negative (positive) values represent increases (decreases) in the forward swap rate. The second column reports the number of data points, while the third and fourth columns display the annualized returns for short and long positions of the equally weighted swaption straddle strategy using Equation (15). The last column shows the annualized return of the equally weighted long-short swaption straddle strategy. The sample period extends from Jun 28, 2013, to April 30, 2022.

Table A7: Extended results: April 2007 to September 2023

	Return(%)	St.Dev(%)	SR
Panel A: April 2007 to April 2022			
3M1Y	3.179	3.264	0.755
3M5Y	4.455	6.689	0.559
3M10Y	4.932	7.756	0.544
Panel B: April 2007 to September 2023			
3M1Y	2.846	3.192	0.575
3M5Y	3.592	6.477	0.398
3M10Y	3.866	7.490	0.381

Notes: This table presents annualized returns, standard deviations and Sharpe ratios for the equally weighted long-short swaption straddle strategy using Equation (15). We assume that investors rebalance the delta hedged swaption straddle position each month. The first two letters in the first column indicate maturity in the short position and the latter two letters display that in the long position. We employ a 10-year tenor. The weight of the long position is obtained as: $q_{equal,L} = 1$ and that of the short position is written as: $q_{equal,S} = -1$. The sample period for Panel A extends from March 31, 2007, to April 30, 2022 and that for Panel B extends from March 31, 2007 to September 29, 2023.

Table A8: Effects of jumps on strategies

	Return(%)	Annual (%)	St.Dev(%)	SR
Panel A: Equally weighted				
Incl. jumps (3M1Y, 20-tenor)	160.4	6.302	6.028	0.927
Excl. jumps (3M1Y, 20-tenor)	146.5	5.931	5.768	0.904
Incl. jumps (3M10Y, 10-tenor)	112.5	4.932	7.756	0.544
Excl. jumps (3M10Y, 10-tenor)	117.0	5.072	7.448	0.585
Panel B: Delta-gamma neutral				
Incl. jumps (3M1Y, 20-tenor)	142.7	5.826	10.57	0.484
Excl. jumps (3M1Y, 20-tenor)	82.96	3.933	10.11	0.318
Incl. jumps (3M10Y, 10-tenor)	114.8	5.004	48.34	0.089
Excl. jumps (3M10Y, 10-tenor)	93.96	4.321	46.13	0.078
Panel C: Delta-vega neutral				
Incl. jumps (3M1Y, 20-tenor)	138.1	5.697	6.036	0.825
Excl. jumps (3M1Y, 20-tenor)	156.0	6.186	5.529	0.990
Incl. jumps (3M10Y, 10-tenor)	51.19	2.675	4.098	0.478
Excl. jumps (3M10Y, 10-tenor)	63.90	3.205	3.808	0.654

Notes: This table presents the effects of jumps. We report daily returns, annualized returns (Annual), standard deviations (St.Dev) and Sharpe ratios (SR) for equally weighted, delta-gamma neutral, and delta-vega neutral strategies. For each strategy, we demonstrate the following four results. The results of “Incl. jumps”, indicate the base results. The results of “Excl. jumps” indicate the results of excluding jump periods detected as changes in daily returns on the spot swap rate are lower than the 0.5th percentile or higher than the 99.5th percentile of the past 1-year values. We employ the following two cases: (i) a 20-year tenor with the swaption maturities of the short position being 3 months and those of the long position being 1 year. (ii) a 10-year tenor with the swaption maturities of the short position being 3 months and those of the long position being 10 years. We use daily data and the sample period extends from March 31, 2007, to April 30, 2022.

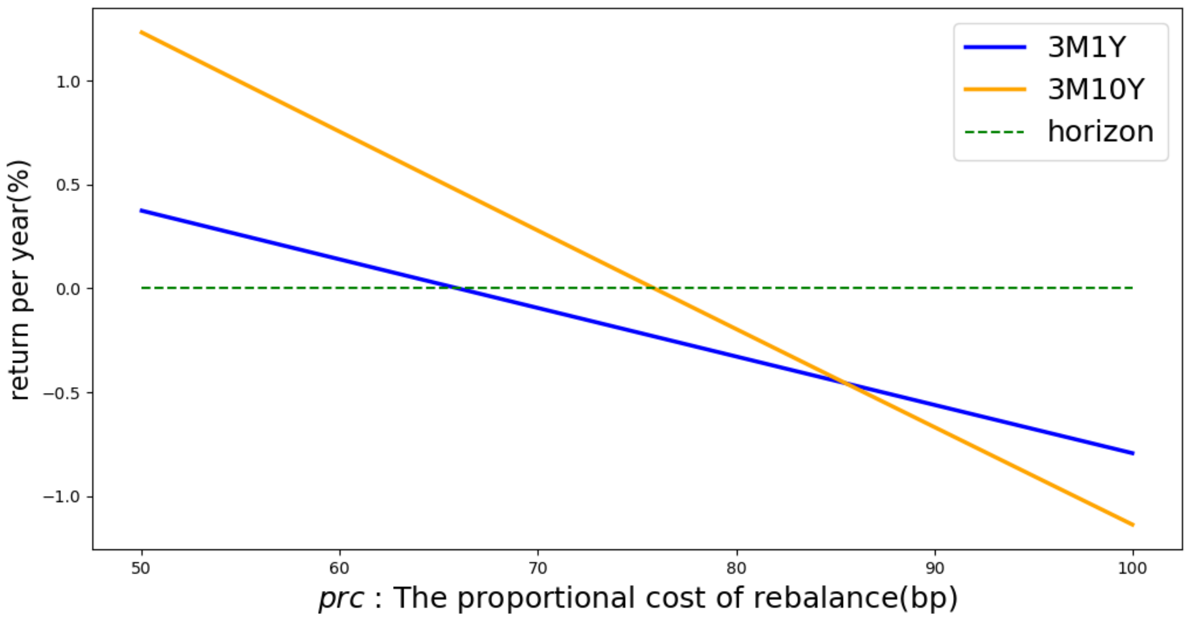

Figure A1. Break-even costs

Notes: This figure displays break-even costs. We focus on a 10-year tenor. We employ the following combination for maturities: 3-month (short) and 1-year (long), and 3-month (short) and 10-year (long). The y-axis demonstrates annualized returns (%) and the x-axis presents rebalance costs *prc* (basis points). We calculate the annualized returns including the *HC*.

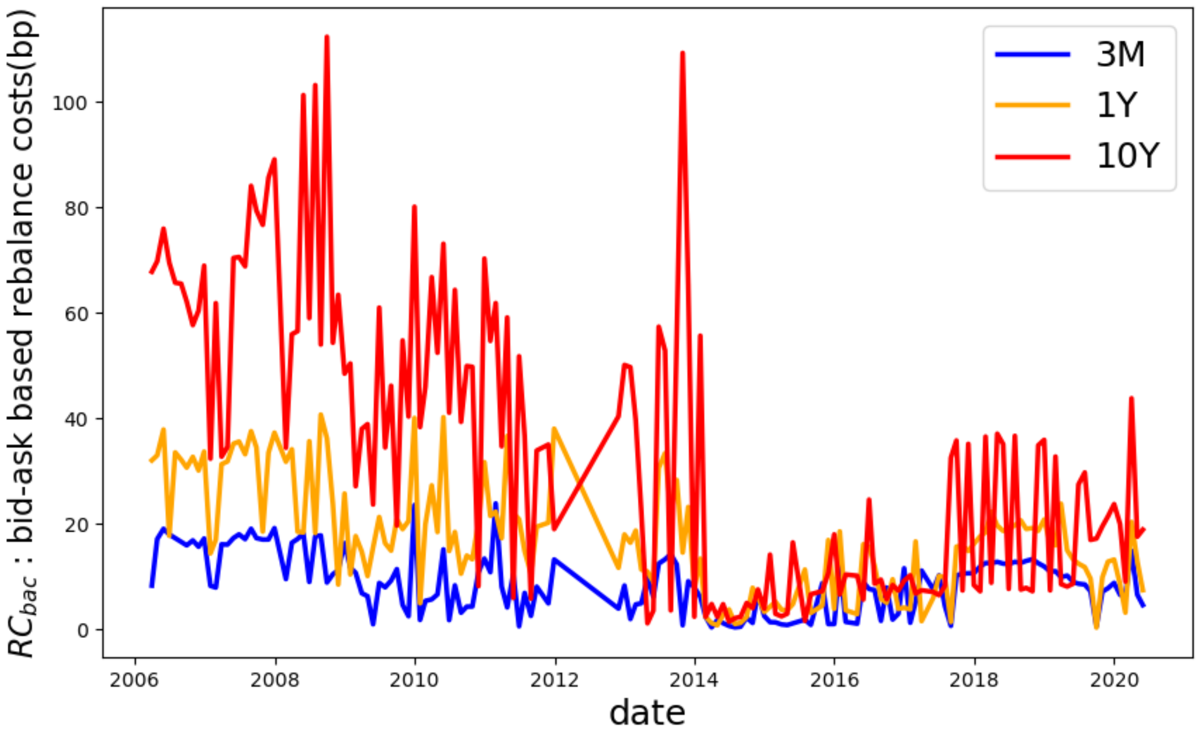

Figure A2. Rebalance costs based on bid-ask spreads

Notes: This figure displays rebalance costs using bid and ask prices on normal volatility. We focus on a 10-year tenor, and 3-month, 1- and 10-year maturities. The y-axis demonstrates the $RC_{bac,t}$ (basis points), which is obtained by Equation (24).

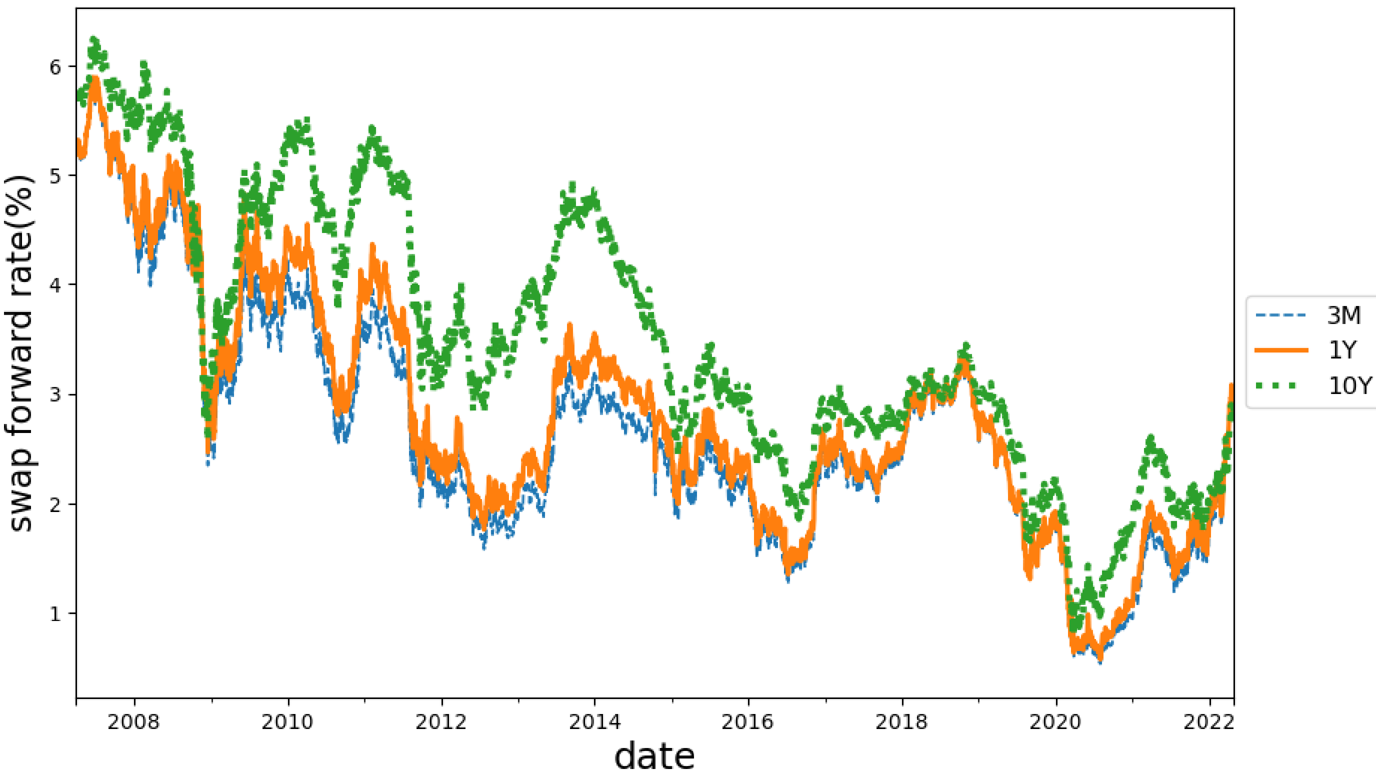

Figure A3. Swap forward rates

Notes: This figure displays the time series of swap forward rates. We focus on a 10-year tenor, and 3-month, 1- and 10-year maturities.

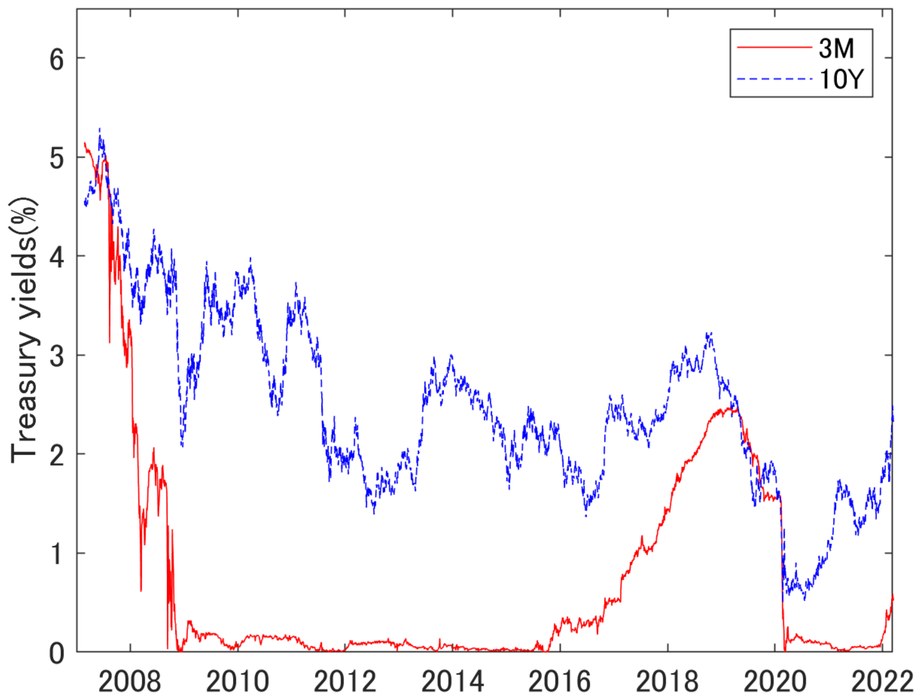

Figure A4. U.S. Treasury yields

Notes: This figure displays the time series of U.S. 3-month and 10-year Treasury yields.

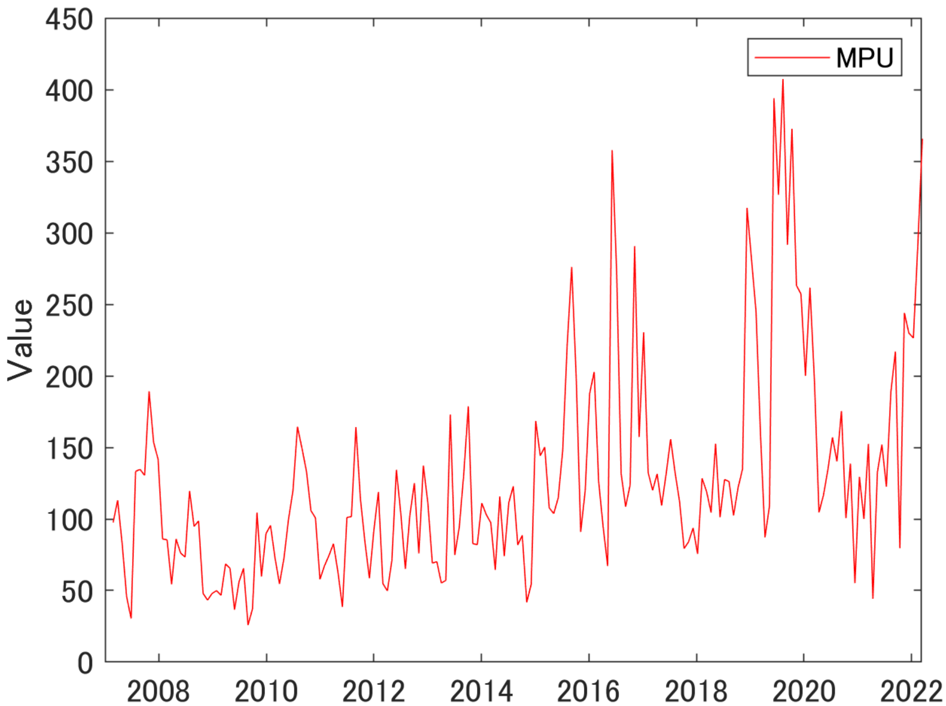

Figure A5. Monetary policy uncertainty index

Notes: This figure displays the time series of the monetary policy uncertainty index proposed by Husted et al. (2020).