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Topics in Yield Curve Modeling

Dissertation thesis

Author: Mgr. Ing. Adam Kučera
Supervisor: Prof. Ing. Evžen Kočenda, M.A., Ph.D., DSc.
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Prague, January 17, 2021

Adam Kučera

Abstract

The aim of the thesis is to examine the interaction of macroeconomic and financial factors through the lens of yield curve dynamics. The thesis consists of three essays that jointly demonstrate the complexity of information incorporated in the yield curve and the importance of attributing yield curve movements to those factors correctly. The first essay uses news-based approach to identify triggers of the U.S. Treasury yield curve movements and demonstrates shifts in the importance of various causes of the movements. The second essay further evaluates the transmission of fiscal policy shocks to the U.S. Treasury yield curve. The first and the second essay together contribute to the literature by showing that the factors beyond the U.S. economic conditions and monetary policy have been becoming an increasingly important cause of the U.S. yield curve movements. These factors include changes in portfolio allocation, cross-border flight to quality and changes in fiscal policy. The third essay proposes a novel method to apply the up-to-date yield curve models to a government bond yield curve in an economy with a relatively shallow government bond market, using the case of the Czech government bond yield curve. This enables decomposing the yield curve and interpreting its movements while accounting for possible specific components in yields at such markets.

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Title	Topics in Yield Curve Modeling
Author's e-mail	`kuceraadam@outlook.com`
Supervisor's e-mail	`evzen.kocenda@fsv.cuni.cz`

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Acronyms

ASWS asset swap spread

BVARX Bayesian vector autoregression model with an exogenous variable

CDS credit default swap

DNS dynamic Nelson-Siegel

DSGE Dynamic Stochastic General Equilibrium

Fed Federal Reserve Board

FPU fiscal policy uncertainty

IRS interest rate swap

SR-SGA shadow rate stationary Gaussian affine

VAR vector autoregression

Chapter 1

General Introduction

The thesis focuses on a yield curve as an important intersection of the fields of macroeconomics, financial economics and public finance. More specifically, the aim of the thesis is to explain the changes in the price of funds, as represented by the yield curve, in terms of interaction among multiple factors. These include, among others, the business cycle, monetary and fiscal policy, shifts in portfolio allocation and international capital flow.

The yield curve—the term structure of interest rates—gathers information about not only historical factors affecting the price of funds in an economy, but also expectations about their future evolution. The extent and the forward-looking nature of information reflected by the yield curve and its shapes imply that it may represent a valuable indicator of business cycle and financial conditions. The slope of the U.S. yield curve, measured as a difference between longer-term and short-term Treasury yields, is a prominent example: economists and financial market participants frequently consider a negative value of the slope as a strong warning of approaching U.S. recession, given the reliability of this indicator (see Estrella & Hardouvelis 1991 for reference and Figure 1.1 for an illustration).[1] The literature explains the accuracy of the slope in predicting recessions by the fact that it includes information about future expected monetary policy, expected inflation and current pricing of risks, all these being dependent

[1] Adrian & Estrella (2008), among others, show that the spread between ten-year and three-month yields is a suitable representation of the slope. Bauer & Mertens (2018) compare spreads using combinations various maturities. They confirm that the difference between ten-year and three-month yields have the best predictive power. However, they also claim that the differences among the predictive power of various spreads are not material and especially highlight the frequent use of the difference between ten-year and two-year yields by market commentators, which is often interpreted as an indicator of interplay between bonds investor and the stance of monetary policy (Bauer & Mertens 2018). The latter spread is used also in Figure 1.1.

on present and expected future business conditions (see Benzoni *et al.* 2018 for reference).

Simultaneously, the variety of factors affecting the yield curve may become a reason for an inaccurate interpretation of (or disability to explain) the causes of yield curve shapes and movements. For example, simplifying the interpretation of the shape of the yield curve to being a consequence of expectations about future evolution of monetary policy may overstate the power of the monetary policy transmission from the short rate to longer rates and further to the economy. Such overstating resulted in so-called Greenspan's conundrum in the U.S. in 2005, when the Federal Reserve Board (Fed) faced unexpectedly declining long Treasury yields despite Fed funds rate increases (Greenspan 2005). The decline was later attributed mostly to changes in term premia (Backus & Wright 2007). Similarly, as discussed in Chapter 4, explaining the negative yields of Czech government bonds solely by monetary policy expectations would be misleading, because temporary cross-border capital flow were an important factor causing the yield decline. Such examples highlight the importance of disentangling the factors affecting the yield curve in order to ensure precise interpretation of its movements. Consequently, the decomposition of the yield curve—splitting yields into multiple components associated with various underlying factors—became an important tool of central banks for understanding the monetary policy transmission.[2] Similarly, the use of unconventional monetary policy tools since the Great financial crisis in some countries was related to the additional yield-driving factors (beyond the present and expected future short rate) that the monetary policies intended to affect in order to ease the monetary conditions.

The knowledge of yield components and ability to interpret the yield curve, its shapes and movements has evolved gradually. The consideration of the interest rates in their term structure rather than as a single variable was present already in the work of Keynes (1930), who discussed the relationship between the short- and long-term rates. Keynes (1936) later described the liquidity premium, i.e., the premium for uncertainty related to holding long-term debts, along with risk premium viewed as a premium for accepting exposure to risk (see Fantacci *et al.* 2014 for detailed discussion). Hicks (1939) subsequently built on the Keynes's concept of interaction among speculators and hedgers and stated that the long

[2]Federal Reserve Bank of San Francisco uses the model of Christensen *et al.* (2011), see *SF FRB web page* for details. Federal Reserve Bank of New York uses the model of Adrian *et al.* (2013), see *NY FRB web page* for details. Example of the Bund yield curve decomposition present Lemke & Werner (2020). The overview of decomposition of the Czech government yield curve as used by the Czech national bank summarizes Chapter 4.

rate may be normally expected to exceed the short rates, where the premium reflects the compensation for the risk of the path of the short rates different than originally expected.

Following the uncertainty about both the extent and the sign of the risk premia as expressed in Keynes (1936), historically, the expectation hypothesis was popular for explaining longer yields as being determined by the expected evolution of short rate, with certain variation in the risk premium expected to partially weaken this relation (Campbell & Shiller 1984). The variation in risk premium was mostly attributed to historical path of the short or long yields or of the level and slope of the yield curve (Shiller 1979)—the risk premium was seen in its narrow definition as a compensation for uncertainty.

The period of yield curve modeling without explicit discussion of external factors behind the yield movements was concluded by a boom in no-arbitrage pricing following widespread adoption of efficient markets hypothesis (Fama & Bliss 1987): the popular no-arbitrage affine model by Duffie & Kan (1996) linked the dynamics of the yield curve to the evolution of three unobserved (latent) factors that were derived from the yield curve itself. The no-arbitrage model by Duffie & Kan (1996) was further expanded by Duffee (2002) by allowing for variation in risk premia. Duffee (2002) has shown that such adjustment is important for explaining the empirically observed excess returns in longer yields, compared to the short yields. Moreover, the no-arbitrage approach to yield curve modeling, as represented by these two pivotal works, implied a shift from the "psychological" view of the risk premium in the sense of Keynes to the view building on the assumption of an absence of arbitrage and the difference between the risk-neutral and risk-averse investors (or probability measures in general). Such view builds on the assumption that if not exposed to risk, each investor earns the yield equal to the short rate, or, over longer horizon, the sequence of short rates. However, in case the investor "locks" the funds into the longer-term investment such as a longer-term bond, he forms own expectations about what the future short rates will be, i.e., he takes the risks that the yield over the investment horizon will differ from the actual sequence of the short rates. If the investor is risk-averse, he will require a compensation for such risk, which is denoted as term premium in the no-arbitrage term structure literature (Duffee 2002). Such view enables the calibration of no-arbitrage affine models and extraction of term premia, because the models work with parameters that link explicitly the short rate dynamics, the variation in the market price of risk and also the excess returns that are empirically observed.[3]

A pivotal examination of explicit linkages between the yield curve and macro-financial factors was presented by Ang & Piazzesi (2003), who use common factors representing price dynamics and business cycle jointly with the latent factors and show that a substantial share of movements of the short end of the yield curve can be explained by the observed factors. The attempts to explain the behavior of the term premium and the long end of the yield curve appeared extensively after the aforementioned proclamation of Greenspan's conundrum. Backus & Wright (2007) claim that the drop in perceived riskiness across asset classes and decreased forward rates of key European government bonds were behind a part of the changes in term premia. Ludvigson & Ng (2009) view the business cycle dynamics and price dynamics as important factors affecting the longer yields. Similarly, Wright (2011) linked the term premium movements with the inflation uncertainty. The effect of the government deficits and the increasing public indebtedness on short and long yields evaluate Dai & Philippon (2005). These efforts are also supported by recent literature that shows that there is an important amount of information about sources of variation in yields and term premium not included in the yield curve itself, i.e., so called *spanning hypothesis* does not hold fully (Joslin *et al.* 2014). Therefore, enriching the yield-only models by observable variables may be beneficial for identifying the causes of yield fluctuations and decomposing the yields correctly.

The thesis fills the gap in the literature concerned with the U.S. Treasury yield curve by providing new evidence on the nature of factors that have been governing the yield curve movements over the last decades. The underlying hypothesis of the thesis is that the factors beyond the U.S. macroeconomic conditions grew in their importance since the end of the last century. The thesis presents evidence supporting the existence of such trend by identifying shift in portfolio allocation, cross-border capital flows (see Chapter 2) and changes in fiscal policy (see Chapter 3) as important sources of yield curve movements over the last two decades. Whereas results of multiple recent studies signaled such finding (see Chapter 2 for a literature overview), there were, to the best of our knowledge, no studies aimed at explicitly stating and quantifying such trend.

[3] The thesis builds on the view by the no-arbitrage asset pricing rather than the macroeconomic (or psychological) view when working with risk/term premia, given the use of no-arbitrage affine models throughout the thesis with the aim of decomposing the yields and obtaining estimates of term premia. See, for example, Duffie (2010) for a description of the core concepts and assumption underlying the asset pricing theory.

Chapter 2 includes the first essay: *Identification of Triggers of U.S. Yield Curve Movements*. This essay observes daily movements in U.S. yields and relates them to the analytic commentaries identified in headlines of financial and economic news reports, which it considers as triggers of the movements. The essay introduces a novel approach to the news-based triggers by seeing them as priors within Bayesian inference. The date, the significance and the impact of the triggers is then updated to comply with the observed yield movements, using Metropolis-Hastings algorithm. The main result of the essay is that the importance of shocks that are not of a business cycle nature, like shifts in portfolio allocation and capital flight to or from the U.S. Treasuries, have been increasing over the last decade. The essay supports such finding with narrative evidence on certain globally important events—the Global Financial Crisis, the eurozone sovereign crisis, the Brexit referendum or the U.S. Presidential election in 2016, for example—and a discussion how these affected the U.S. Treasury yields, using also a what-if counterfactual analysis.

The chapter was published as an article in the North American Journal of Economics and Finance.

Kučera, A. (2020): Identification of triggers of U.S. yield curve movements. *The North American Journal of Economics and Finance*, Volume 54, 2020, No.101288

Similar motivation—to focus on yield curve factors beyond business cycle fluctuations—was pursued in Chapter 3: *Yield Curve Dynamics and Fiscal Policy Shocks*. The essay uses a variety of VAR models to demonstrate the effects of fiscal policy shocks on the U.S. Treasury yield curve. The various models differ in both the way how the fiscal policy shocks are identified (and which fiscal variables enter the model) and the way how the yield curve is represented in the particular VAR model. The essay identifies the fiscal policy shocks in three ways, including (i) the canonical approach by Blanchard & Perotti (2002), which uses the actual government spending figures, (ii) the forward-looking expectations about future changes in fiscal policy using the CBO (2020) government spending projections, motivated by results of the narrative approach by Ramey (2011), and (iii) a Dynamic Stochastic General Equilibrium (DSGE) model-based identification of the government spending shocks. The yield curve is represented either (i) by the Fed funds rate and the five-year Treasury yield, (ii) by the level, the slope and the curvature of the yield curve using the Nelson & Siegel (1987) function and (iii) by a set of yield factors that are identified within a complex affine term structure model by Bauer & Rudebusch (2020). The combination of the results provided by the individual VAR models shows in a robust way that expansionary U.S. fiscal policy innovations at the time they are announced or became expected result in a temporary drop in yields due to an increased uncertainty, which transmits through both the real economic conditions and the flight-to-quality behavior. After several quarters when the government spending shock is realized and financed on the markets, we match the findings in the literature by confirming that the initial drop in yields is exchanged for an increase due to a combination of a real impact of the expansionary fiscal policy on the aggregate demand and the real activity and the transmission through the financial markets' response—an increase in the risk premia due to uncertainty about the fiscal sustainability and the shift in the Treasury bond supply causing the increase in yields on the primary and secondary Treasury markets and possibly also a crowding-out effect.

> The preliminary version of the chapter was published as a working paper at the National Bank of Slovakia, co-authored with Evžen Kočenda and Aleš Maršál.
>
> Kučera, A., Kočenda, E. & Maršál, A. (2019): Yield Curve Dynamics and Fiscal Policy Shocks. *National Bank of Slovakia Working and Discussion Papers*, 2/2019, Research Department, National Bank of Slovakia.

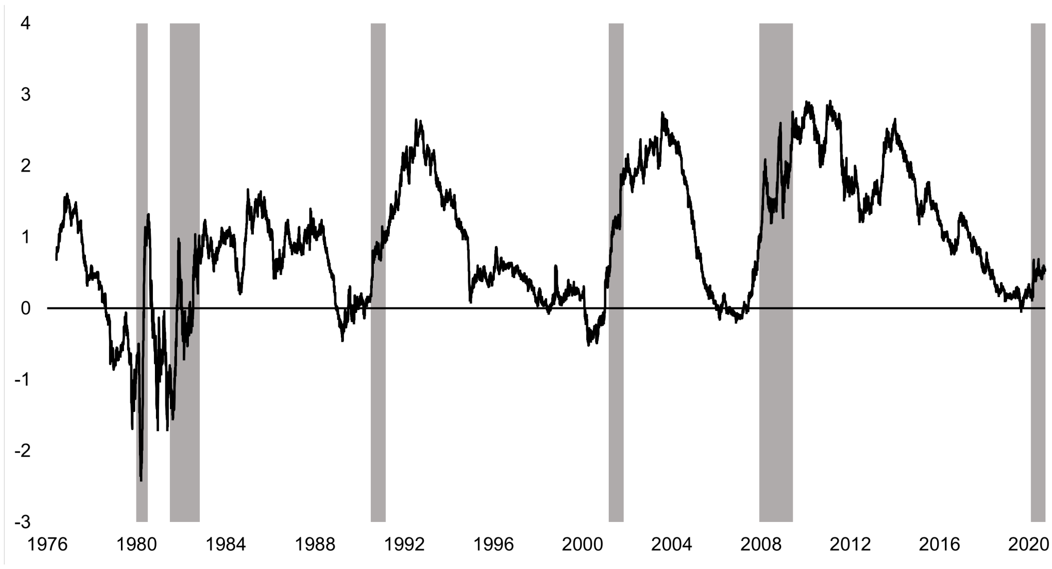
The third essay partially builds on the findings of the first essay. Most of the literature focuses on yield curves in the largest economies, as the specificities of government bond markets in smaller economies, mostly unrelated to business cycle dynamics, may imply invalidity of the assumptions of canonical yield curve models. Chapter 4—*The Czech Government Yield Curve Decomposition at the Lower Bound*—fills this gap and contributes to the literature by proposing a method to improve the decomposition of the government bond yield curve in a small economy with a relatively shallow government bond market, as is demonstrated on the case of the Czech market. The essay proceeds by applying the decomposition using canonical affine yield curve model on the term structure of Czech koruna interest rate swap (IRS), which is generally less affected by the specific factors affecting the yields in the small open economy. The decomposition of the Czech government bond yield curve is obtained by adding additional components, namely credit risk premium and portfolio effect. Such adjustment allows obtaining unbiased decomposition and interpretation of the Czech yield movements.

The chapter was published as an article in the Czech Journal of Economics and Finance, co-authored with Michal Dvořák and Zlatuše Komárková.

Dvořák, M., Komárková, Z. & Kučera, A. (2019): The Czech Government Yield Curve Decomposition at the Lower Bound. *Czech Journal of Economics and Finance*, Charles University Prague, Faculty of Social Sciences, vol. 69(1), pages 2–36, February 2019.

The thesis is structured as follows. The three essays are presented in Chapters 2–4. Afterwards, each of the chapter is accompanied by an appendix. Finally, Appendix D includes overview of responses of the author to the referees' comments.

Figure 1.1: Slope of the U.S. Yield Curve (in percentage points)



Source: FRB (2020)

Note that the slope is measured as a difference between ten-year and two-year Treasury yields. The shadow areas represent the U.S. recessions as dated by the National Bureau of Economic Research.

Chapter 2

Identification of Triggers of U.S. Yield Curve Movements

2.1 Introduction

There is a clear dichotomy in views on U.S. Treasury yields in the literature. From one perspective, since the pivotal works of Ang & Piazzesi (2003) and Diebold *et al.* (2006), macroeconomic factors are viewed as the main source of volatility in yields. The yield curve is a benchmark for the cost of funds at various maturities, and yields are, therefore, macroeconomic variables directly linked to monetary policy and the business cycle. On the other hand, and simultaneously, a yield is linked to the price of the bond, which is a financial instrument with its supply and demand being affected by various additional factors. The importance of factors beyond U.S. macroeconomic conditions has been documented, among others, by Bernanke *et al.* (2004), Dai & Philippon (2005), Craine & Martin (2009) or Byrne *et al.* (2012). This dichotomy may present challenges when interpreting the shapes and dynamics of yield curves. Understanding the factors driving yield curve movements is therefore crucial for their correct interpretation.

To do so, we adopt a novel approach to attribute movements in the U.S. Treasury yield curve to various sources. Using news headlines, we identify prior candidates for dates when yields were affected by news in a certain category: Fed announcements, macroeconomic news, Treasury auctions, financial market news and geopolitical uncertainty news that induced cross-border capital flight. Using a Bayesian approach, we update these dates and the magnitude of the impact of the news, which allows us to measure the degree to which the individual categories contributed to the historical variation in the yields.

Our approach is further motivated by several underlying issues. For instance, the interpretation of yield curve inversion as an indicator of a forthcoming crisis implicitly regards a shift in expectations about future monetary policy as the only source of the inversion. This interpretation may neglect the impact of events that motivate international capital flight to U.S. Treasuries as a safe haven, which may be only loosely related to U.S. macroeconomic conditions. The importance of correctly interpreting yield curve movements is also apparent from the historic experience with monetary policy challenges. In 2005, Fed chairman Alan Greenspan expressed the conundrum he faced given the decoupling of movements in short- and long-term yields. Foreign demand for U.S. Treasuries was identified as one of the most important causes of such decoupling (see, for example, Bernanke *et al.* 2004 or Byrne *et al.* 2012). Similarly, in 2017, the conundrum was partially revived, when the increase in short-term yields was only loosely followed by the movements in long-term yields. Again, non-macroeconomic forces were mentioned as an important source of decoupling (Bauer 2017).

We accompany the evidence on the importance of causes of fluctuations in U.S. yields beyond U.S. macroeconomic conditions from the literature by own narrative news-based observations. As we demonstrate using news headlines, the recent global events inducing uncertainty such as eurozone debt crisis, Brexit referendum or global trade tensions resulted in significant cross-border capital flight seeking U.S. Treasuries as a safe haven. The extent of the international capital flight has been largely debated over the last decade (Avdjiev *et al.* 2020), closely linked with global search for yield related to the low yield environment (see Ammer *et al.* 2018, for instance). Similarly, the sensitivity of the cross-border capital flight on non-macroeconomic events increasing the uncertainty has been documented in the literature (Julio & Yook 2016). All these pieces of evidence serve as the core motivation of our research: to confirm the existence of a trend of growing importance of capital flight (and events unrelated to U.S. macroeconomic conditions in general) for explaining U.S. Treasury yield movements and to quantitatively evaluate the extent of these linkages.

We analyze triggers of yield curve movements by using a state-space representation, which may be seen as a combination of the dynamic Nelson-Siegel (DNS) model developed by Diebold & Li (2006) and a time-varying parameter regression model. Unlike the DNS model, the innovations in yields are included in our model as exogenous variables in the measurement equation. The transition equation captures the dynamics of the magnitude of how these innovations impact the yields. The innovations (triggers) are considered stochastic, as we combine priors gathered from news headlines with the likelihood of yield curve movements to obtain the posterior distribution of the innovations. Our method may be seen as complementary to the canonical DNS model; whereas the canonical DNS model identifies the "original" orthogonal shocks responsible for the deviation of yields from their steady-state values, our methods identify innovations in the form of triggers of movements related to how the original shock propagates over time into the yield curve.

Our results show that both macroeconomic and non-economic events are important triggers of yield curve movements. We assign the movements in the U.S. Treasury daily yield curve between December 2000 and June 2019 to the aforementioned categories. We show that an increasing proportion of the movements in longer yields was triggered by news about geopolitical risk or economic conditions abroad. Most important, over the last decade, these events became the dominant source of yield fluctuations, as they included developments in the eurozone debt crisis, capital flight following the Brexit referendum or international trade tensions.

The remainder of the paper is structured as follows. We position this paper in the literature in the second section. The third section presents data used, stylized facts about recent dynamics in U.S. Treasury yields and the narrative context of the largest movements. We describe our approach to identifying the innovations and evaluating their attribution to U.S. yield movements in the fourth section. The fifth section presents and discusses the results of the quantitative analysis and demonstrates their implications using a counterfactual analysis. Finally, the last section concludes the paper.

2.2 Literature Review

The paper contributes to the term structure literature in two ways. First, it emphasizes that non-macroeconomic variables[1] can also bear an important amount of information unspanned by the U.S. yield curve. This section sum-

[1]Note that the term "non-macroeconomic" is related to the U.S. Treasuries market. That means that foreign macroeconomic events are also considered as non-macroeconomic from the perspective of this chapter.

marizes the background behind this motivation and studies from the literature focused on macrofinancial modeling and the identification of macrofinancial yield curve factors. The most important findings from the literature are that (1) it is justifiable to extend the term structure model by observable factors, but (2) only macroeconomic variables are usually used for the extension. The second contribution of this paper is a novel means of attributing yield curve movements to yield innovations.

In a pivotal work in the macrofinancial modeling of interest rates, Ang & Piazzesi (2003) extend the canonical Gaussian no-arbitrage affine term structure model of Duffie & Kan (1996) to include macro factors and show that this extension provides important additional information about the nature of the yield movements. As an alternative approach lacking the no-arbitrage assumption, Diebold *et al.* (2006) extend the DNS model of Diebold & Li (2006) by including macroeconomic factors and demonstrate linkages between the macroeconomic factors and the yields.

These works led to the creation of a first generation of macrofinance models. The macroeconomic factors included in the macrofinance models usually represent business activity, price dynamics and a monetary policy rate or monetary aggregate. Ang & Piazzesi (2003) utilize two measures representing inflation and real activity and show that whereas these factors are responsible for most movements at the short end of the yield curve, the long end remains largely unexplained. Diebold *et al.* (2006) use manufacturing capacity utilization, the Fed funds rate and annual price inflation. Ludvigson & Ng (2009) and De Pooter *et al.* (2010) utilize a large dataset that includes macroeconomic and financial variables and extract the most important principal components representing the common factors. Based on their relation to the original series, De Pooter *et al.* (2010) show that the first principal component is roughly related to real activity, the second component to price dynamics and the third component to monetary variables. Similarly, Kim & Wright (2005) study the specific role of inflation in explaining yield dynamics. As an additional view, Dai & Philippon (2005) focus on the importance of fiscal policy for explaining the dynamics of U.S. yields.

In an important contribution, Joslin *et al.* (2011) question the validity of such macrofinance models. The authors demonstrate that without additional restrictions in the transition equation, macrofinance models are equivalent to yield-only models. Therefore, as they argue, the canonical macrofinance models cannot provide additional information important for forecasting yields, as the models contain the embedded assumption that the macro factors are perfectly spanned by the yield curve. Joslin *et al.* (2014) show that such an assumption is not valid, i.e., there is important information on the macro variables not included in the yield curve. As a solution, Joslin *et al.* (2014) develop a new family of macrofinance yield curve models with unspanned macro variables that affect the price of risk and show that such models can be used to improve forecasting abilities and in-sample properties compared to yield-only models. Although the validity of the evidence supporting the *unspanned hypothesis* is partially called into question by Bauer & Hamilton (2017), it generally remains acknowledged that it is justifiable to extend the term structure models to include macroeconomic factors using either unspanned macro variables or a set of restrictions on the transition equation. The latter approach is utilized in more recent contributions by Cieslak & Povala (2015) and Bauer & Rudebusch (2020), who show that the yields, risk premia and excess returns may be well explained by models with specific transition equation constraints that permit one to distinguish cycles and trends in inflation and the real rate as yield factors.

Multiple studies have focused on understanding the factors behind the movements in the term premium and bond excess returns instead of capturing the dynamics of the yield curve as a whole. Campbell & Shiller (1991) and Cochrane & Piazzesi (2005) demonstrate the partial predictability of excess bond returns using Treasury yields and forward spreads. These findings underline the importance of term premia for understanding yield dynamics. The possible decoupling of long and short yields due to a variation in term premia was extensively discussed after the testimony of Alan Greenspan in 2005, where the Fed chairman admitted that he faced a conundrum of declining longer yields despite restrictionary monetary policy steps. Backus & Wright (2007) demonstrate that multiple factors were responsible for this decoupling, all of which affected the yields through a decrease in term premia. Ludvigson & Ng (2009) demonstrate that macro factors (output and price dynamics) are responsible for the countercyclicality of the term premia. Similarly, Wright (2011) reveals a linkage between bond risk premia and inflation uncertainty. The relation between the risk premium and economic risks is also inherent in the structural approach to yield curve modeling, as in Rudebusch & Swanson (2012).

Importantly, the literature only rarely contains analyses of the linkages among bond yields, term premia and/or excess returns and non-macroeconomic factors. Of the aforementioned contributions, Dai & Philippon (2005) focus on the effects of fiscal policy. Bernanke *et al.* (2004), Craine & Martin (2009) and Byrne *et al.* (2012) all link the decline in term premia underlying Greenspan's conundrum to the effect of international portfolio reallocations towards U.S. Treasuries. Bauer (2017) highlights the decreasing longer-term yields despite increasing Fed funds rate between 2015 and 2017 and concludes that the revived conundrum was caused by a combination of decreasing inflation expectations, fiscal policy shocks and geopolitical uncertainty effects, explicitly mentioning the declines in U.S. Treasury yields on days with news headlines about tensions with North Korea.

We build on these latter efforts to emphasize the effects of non-macroeconomic factors when explaining yield movements. In doing so, our aim is to contribute to the literature by providing empirical evidence proving that, similar to the benefits of adding macroeconomic variables into the models, it can also be beneficial to add non-macroeconomic variables, especially for understanding yield variations at higher frequencies.

2.3 U.S. Treasury Yield Movements and News Headlines

This section gathers several stylized facts about daily U.S. Treasury yield movements between December 2000 and June 2019.[2] We identify historical yield movements and summarize related news headlines. We show initial narrative findings related to the density of various categories of factors as mentioned in the headlines, which serves as a motivation for the quantitative analysis in the rest of the paper.

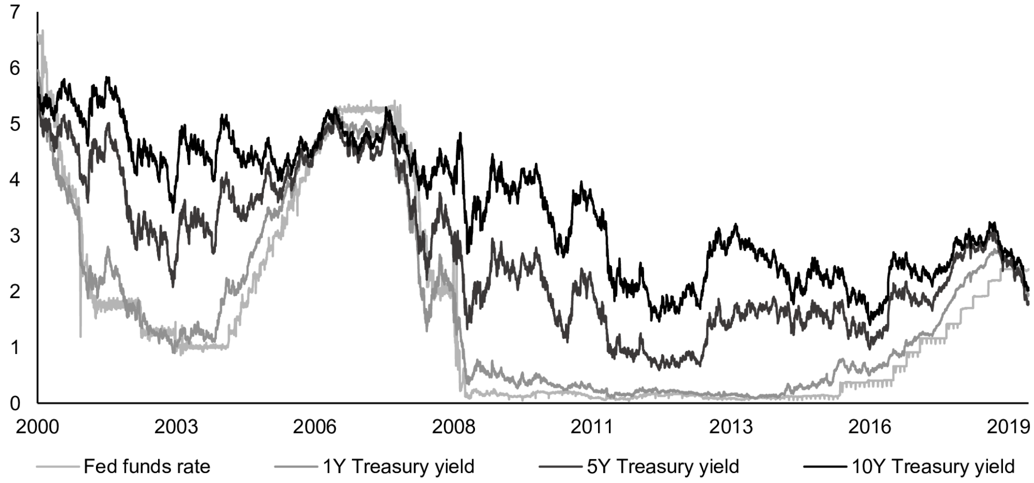
We use daily U.S. Treasury yield data from Fed (2019) for the period between December 4, 2000 and June 28, 2019.[3] This period was selected as optimal given its homogeneous news data coverage, which we demonstrate below. The historical paths of yields for selected maturities are displayed in Figure 2.1; basic

[2]The short-term yields were close to the lower bound over a significant part of the period of analysis. The lower bound proximity makes the results of canonical yield curve models utilizing symmetric stochastic processes biased. We avoid this by using a different modeling approach (see Section 2.4) and focusing on the differences of yields instead of yield levels. Therefore, from the econometric point of view, our results are unbiased. The lower bound proximity can, however, bring certain challenges when interpreting the dynamics of the slope factor and its sensitivity to innovations during the low yield periods.

[3]Yields were not seasonally adjusted. We expect a possible seasonality in yields to be sufficiently reflected by the corresponding seasonality in the news reports that we use to explain the yield dynamics. The yields were not detrended – possible non-stationarity of the yield time series is addressed by using yields in the first differences instead of levels.

descriptive statistics are displayed in Table A.1 in Appendix A. Over the period of analysis, the longer yields followed a downward trend. The short-term yields fluctuated around the trend along with the business and monetary policy cycle, including periods of both restrictive monetary policy (2000, 2005–2007, partially since 2017) and monetary loosening (2001–2004, 2008–2016).

Figure 2.1: U.S. Treasury Yields (in %, 2000/12–2019/06)

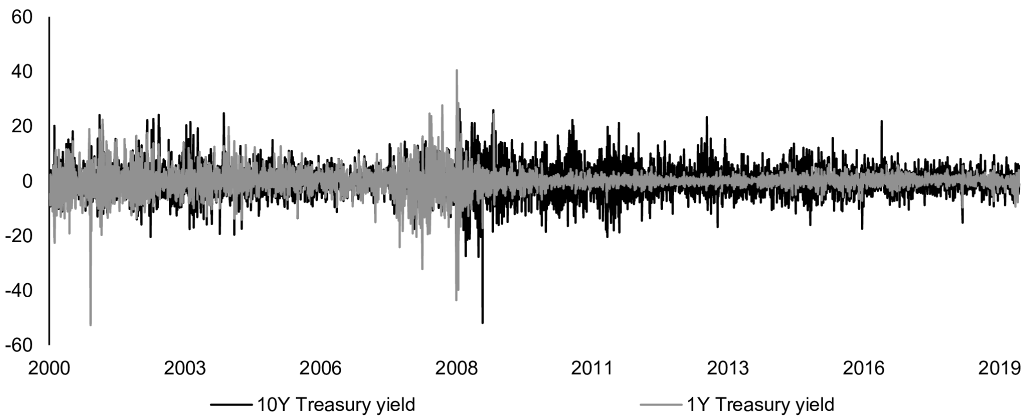


Source: Fed (2019)

The realized or expected changes in monetary policy were an important source of the daily volatility of short-term yields, with the cluster of increased volatility observed over the period 2007–2008 (see Figure 2.2) being directly attributable to a period of sizable changes in the Fed funds rate (see Figure 2.1). Unlike the short-term yields, the spikes in longer yield daily movements were often related to non-macroeconomic events. Increased volatility in longer yields appeared after the outbreak of the Great Recession in September 2008. Most important, the three largest 10Y Treasury daily movements since 2016 were linked to non-macroeconomic news (see Table A.2 in Appendix A and the description of the source of the news reports below). The result of Brexit referendum in June 2016 led to a decline in the U.S. yields that was attributed by news reports to an international flight to quality; the result of the U.S. presidential election in late 2016 was mostly attributed to a combination of expectations about a fiscal impulse and a rise in risk premia, and the May 2018 uncertainty over Italian fiscal sustainability sparked a renewed flight to quality and subsequent decline in U.S. Treasury yields.

To identify the triggers of the yield movements and measure their importance,

Figure 2.2: Daily Changes in U.S. Treasury Yields (in bps, 2000/12–2019/06)



Source: Fed (2019)

we gather economic news headlines through the News Monitor application on the Refinitiv EIKON platform. Specifically, we gather headlines that (i) mention U.S. Treasury bond prices or U.S. Treasury yields, (ii) describe the direction of their movement and (iii) state some source of the movement (for details, see Appendix A). By applying this filtering, we obtain 9,100 news headlines. We further evaluate each headline and remove duplicates and headlines that, despite satisfying the filtering criteria, do not provide sufficient information, which reduces the number of usable headlines to 3,065 that explicitly state causality between some trigger and a direction of the daily movement of the yield or the bond price. Thereafter, by observing the most frequently mentioned sources of the movements, we define five categories of triggers. We once again observe each headline, or even read the text of the article, to correctly assign the trigger of the yield movement to the particular category. The first category gathers the triggers linked to fiscal policy-related events, mostly Treasury auctions. Second, Fed announcements mentioning either conventional or unconventional monetary policy steps are frequently mentioned in headlines as a source of the yield movement, especially when the announcements included a surprise. The third category includes the U.S. macroeconomic news and represents the most common cause attributed to daily yield fluctuations. Events affecting the rest of U.S. financial markets, especially the equity market, were responsible for intra-U.S. flight to/from quality (the fourth category), whereas international events changing the attitude of global investors towards risk often triggered cross-border safe haven flight into or from U.S. Treasuries (representing the triggers in the fifth category). The list of keywords used to map the headlines to these categories is included in Appendix A.[4]

The frequency of news reports in various categories is shown in Table 2.1. As the table shows, the frequency of reports was relatively stable over the period of analysis, which is important given the possible changes in news providers or the reach of the source database. Over the period of analysis, at least two headlines were identified almost every week, which may serve as a good basis for covering the most important historical movements in yields. Because we focus on the relative importance of news in various categories, the accuracy of headline filtering is more important than the number of identified events. In other words, we applied rather strict filters, ensuring that the headlines that pass the filters correctly identify the nature of the trigger (the category), at the expense of losing some in-sample fit. This has consequences for the results of our quantitative analysis, as we demonstrate in the next sections: the yield movements in periods of less-volatile bond markets and no significant innovations are only partially explained by our model because the news is non-informative over these periods. On the other hand, important events, which triggered large shifts in yields, are believed to be identified by the news headlines with sufficient precision.

The frequency of headline categories shows gradual growth in the triggers related to capital flight over the observed period. This supports the hypothesis proposed by this paper that the factors affecting U.S. Treasury yields through their role in global portfolios became stronger over time. The number of published news items itself does not imply stronger effects in terms of yield movements. However, a detailed examination of the headlines during periods of increased yield volatility further supports the hypothesis. We identify the largest daily gains and declines in the ten-year U.S. Treasury yields each year and find headlines linked to the days of the movements (see Table A.2 in Appendix A). Fed meetings, macroeconomic data announcements and treasury auctions were the topics most frequently linked in news headlines to the largest yield movements between 2001 and 2010. Since 2011, however, non-macroeconomic events triggered some of the largest movements. As an additional evidence, we also evaluate the correlations between the selected yields and the dummies for news headlines on particular days (see Table A.1 in Appendix A). The

[4]Note that one headline may contain keywords for multiple categories. For example, news articles interpreted the surprising result of the 2016 U.S. presidential election as both a macroeconomic trigger and an international capital flight trigger. As we describe below, such headlines represent multiple priors for the triggers (innovations) in each of the mentioned categories.

Table 2.1: News Headline Frequency

	Fiscal policy	Fed surprise	Macro news	Financial market	Capital flight	Total
Average monthly number of headlines						
2001–2005	0.72	2.17	5.87	4.38	1.55	14.68
2006–2010	0.98	1.48	5.08	2.35	1.75	11.65
2011–2015	1.72	2.58	6.93	2.65	2.90	16.78
2016–2019	2.74	3.76	7.05	4.64	5.05	23.24
Share of headlines per category (in %)						
2001–2005	4.88	14.76	39.95	29.85	10.56	
2006–2010	8.44	12.73	43.63	20.17	15.02	
2011–2015	10.23	15.39	41.31	15.79	17.28	
2016–2019	11.78	16.19	30.33	19.98	21.72	
Total number of headlines						
Frequency	320	532	1,369	758	584	3,563
Share (in %)	8.98	14.93	38.42	21.27	16.39	

Source: News Monitor at EIKON – Refinitiv, author's calculations.
Note that the presented total number of headlines for all categories (3,565) is larger than the number of originally obtained headlines (3,065) since some headlines included keywords from multiple categories and therefore served in the quantitative analysis as multiple priors (see the next section for details).

results show that the correlations between yield movements and presence of news headlines are comparable across all categories under consideration except for the fiscal policy. Therefore, the yields movements may be expected to be triggered by macro news and non-macroeconomic events equally frequently. The remainder of the paper quantitatively evaluates this hypothesis, measuring both the effect of changes in the frequency of various categories of triggers and the linkage between yield volatility and news headlines.

2.4 Methodology

This section summarizes the method we use to quantitatively evaluate the aforementioned intuition and hypothesis. To do so, we use a time-varying parameter regression model with elements of the DNS model. The model consists of three building blocks that link the daily change in yield $y_t(\tau)$ with maturity τ to the presence of an innovation (a trigger), which we obtain from the news headlines.[5]

[5] Above, we have used the term "trigger" to describe a new piece of information regarding the cause of a yield movement obtained from the news. In the text below, where we introduce

First, the model reduces the dimension of the yield curve by using several common factors to parametrize the whole yield curve. We obtain the factors using the Nelson & Siegel (1987) representation of the yield curve. This representation is linear in the factors, which allows us to use it directly to capture the dynamics of the first differences of yields, which are our focus, instead of the levels of yields. Therefore, we represent the daily change in the yield curve $\{dy_t(\tau)\}_\tau$ by a change in three common factors $\{dF_{f,t}\}_{f=1,2,3}$ as follows:

$$dy_t(\tau) = \sum_{f=1}^{3} L_f(\tau)\, dF_{f,t} + \nu_t(\tau) \ . \tag{2.1}$$

The factor loadings

$$L(\tau) = \left[1 \ , \ \frac{1-e^{-\lambda\tau}}{\lambda\tau} \ , \ \frac{1-e^{-\lambda\tau}}{\lambda\tau} - e^{-\lambda\tau}\right] \tag{2.2}$$

are functions of τ and a fixed parameter λ, which we set to 0.0821 to ensure an optimal fit, minimizing the fitting error $\nu_t(\tau)$. We also considered the value 0.0609 presented in Diebold & Li (2006) and obtained very similar results. Following the functional forms of the factor loadings with respect to the maturity, the factors $F_{f,t}$ can be referred to as a level, a slope and a curvature of the yield curve.

The second building block of the model is the linkage between the changes in factors $dF_{f,t}$ and the observed innovations $x_{c,t}$ for the innovation categories $c = 1, 2, ..., C$. We link them using linear regression with time-varying parameters $\beta_{c,f,t}$:

$$dF_f, t = \sum_{c=1}^{C} \beta_{c,f,t} x_{c,t} + \upsilon_{f,t} \ . \tag{2.3}$$

As the time-varying parameters are factor- and category-specific, the total number of these parameters is $3C$. The combination of (2.1) and (2.3) provides the final measurement equation of our model:

$$dy_t(\tau) = \sum_{f=1}^{3} L_f(\tau) \sum_{c=1}^{C} \beta_{c,f,t} x_{c,t} + \epsilon_t(\tau) \ . \tag{2.4}$$

the model, we also use the term "innovation" to highlight the econometric approach we employ to quantitatively estimate the impact of these triggers. Nevertheless, throughout the paper, the two terms are considered equivalent and used interchangeably.

The measurement error $\boldsymbol{\epsilon_t} \sim \boldsymbol{N}\left(\mathbf{0}, \boldsymbol{R}\right)$ is given as a combination of the fitting error $\boldsymbol{\nu_t}$ from (2.1) and a sum of the regression errors for the three factors $\sum_{f=1}^{3} L_f \boldsymbol{\upsilon_{f,t}}$ from (2.3). For simplicity, we assume the errors to be mutually uncorrelated.

To complete the model, we formulate a transition equation for the time-varying parameters $\{\beta_{c,f,t}\}_{f=1,2,3;c=1,2,\dots,C}$. We gather the parameters in a $3C$-dimensional vector $\boldsymbol{\beta_t}$ assumed to follow a random walk:

$$\boldsymbol{\beta_t} = \boldsymbol{\beta_{t-1}} + \boldsymbol{\eta_t} \ , \tag{2.5}$$

where $\boldsymbol{\eta_t} \sim \boldsymbol{N}\left(\mathbf{0}, \boldsymbol{Q}\right)$ represents the random disturbances in the transition equation. Together, (2.4) and (2.5) form a state-space representation of the dependency of yield movements on the appearance of an innovation from category c. As is common in the state-space framework, we assume the random vectors $\boldsymbol{\epsilon_t}$ and $\boldsymbol{\eta_t}$ to be mutually unrelated.

Our method may be seen as complementary to the canonical DNS model, rather than competitive. In the DNS framework, the yield curve shocks are identified as innovations in processes of the latent or observable factors $\widetilde{F}_t$, which themselves enter the transition equation. Since Diebold & Li (2006), the joint dynamics of these factors have typically been specified as a stationary VAR process that allows the shocks to propagate gradually. A possible explicit inclusion of macrofinancial series into the joint dynamics of the factors, to explain the macrofinancial linkages, is presented by Ang & Piazzesi (2003), Diebold *et al.* (2006), De Pooter *et al.* (2010) and Joslin *et al.* (2014). In these works, the inclusion of macro series implies that the model may be specified on a monthly or quarterly frequency, for which the macro series are available. This is useful for considering a macroeconomic perspective of the yield curve, because it, together with the stationary VAR process, allows the researcher to capture the gradual propagation of the initial shock into business cycle dynamics, the monetary policy rate and the gradual response of the yields. However, the financial view of the yield curve may suffer from the use of the monthly data because (i) a liquid financial market, including the treasury market, is expected to adjust prices almost immediately, and (ii) an important part of the information about the yield movements between two end-of-month observations may be lost. In other words, using the monthly frequency may result in an aggregation and a mutual compensation of multiple sources of yield movement within a single month, which would imply an underestimation of the importance of certain events.

Therefore, to be able to evaluate the daily movements of yields, we include the innovations in yields as exogenous variables $x_{c,t}$ in the measurement equation (2.4). The transition equation (2.5) then captures the dynamics of the magnitude of how these innovations impact the yields. The need for daily data further explains why we obtain information about innovations from news headlines instead of macro series.

To illustrate the linkage between our and the canonical DNS approach, it can be highlighted that the shocks in the DNS approach (appearing in the transition equation) and the innovations in our approach (the triggers of the movements in the measurement equation directly affecting the yields) would be equivalent under three conditions. First, the markets have to be efficient, i.e., correctly anticipate and price future consequences of the shocks, given the information available at the time of the shock. Second, the maturity of the bond has to be longer than the horizon of the shock propagation. This condition ensures that the expected gradual propagation of the shock in the DNS approach is fully reflected in the change of the yield, equivalently to the one-off adjustment following the innovation in our approach. Third, the yields must not be mean reverting after the initial impulse, because our model assumes one-off change in yields after the innovation appears, without any future reversal. The third theoretical condition is the most questionable, as the yields are frequently considered to converge to a long-term equilibrium, although this view has been recently questioned (Bauer & Rudebusch 2020).

For example, an unexpected adverse demand shock may lead to temporary decrease in the monetary policy rate, ceteris paribus. The monetary policy authority may respond with a lag, subject to its policy function and the gradual impact of the adverse shock on inflation. The short end of the yield curve evolves together with the path of the monetary policy rate. In the DNS approach, this evolution would be modeled as a gradual transition of the factors $\widetilde{F}_t$ and, subsequently, of the yields, following the single initial shock to one of the factors. In our approach, the dynamics would be captured as a series of innovations $\{x_{c,t}\}_{t=1,2,\dots}$ that together represent gradual adjustments of monetary policy rate and other related effects. This is the consequence of the duration of the shock propagation being longer than the maturity of the bond at the short end of the yield curve.

However, in the case of the long end of the yield curve, efficient markets would imply that all the future expected monetary policy rate adjustments and changes in risk premia would immediately be priced in the bond yields, given that the entire transition effect occurred before the maturity of the bond. In both the DNS and our approach, this would imply a one-off jump adjustment in the yield. If the DNS model is specified as stationary, it then implies a gradual return of the yields to their steady state. In our approach, the possible return to the steady state represents new information and is therefore linked to a new innovation x_t.

The view forms our interpretation of the results. Our interpretation focuses on the news headlines as signals of an existence of triggers that influence the yields along the path they follow. For long yields, these triggers may therefore be considered as almost equivalent to the initial shocks, whereas for the short yields, these triggers are rather indicators representing whether the initial shock propagates as expected.

Finally, **the third building block** includes the method of how the innovations $x_{c,t}$ are obtained. We use the news headlines introduced in the previous section. News-based identification of an innovation may be inaccurate due to either an imprecise timing of the article (reports published on a certain day may either reflect the current day or be an ex-post commentary on the situation from the previous days) or an incorrect opinion of the analyst regarding the nature of daily yield movements. We therefore view the innovations (the triggers) as stochastic, where the day of the publication of a headline represents the mean value of a prior distribution of the day when an innovation in the given category may appear (regarding t in $x_{c,t}$). Using the Bayesian approach, we combine such priors gathered from the news headlines with the likelihood of yield curve movements to obtain the posterior distribution of the *location* of the innovations. Specifically, we use a normal distribution centered on the date that each headline was published with three business days' standard deviation as the prior distribution for each innovation location.

The filtering criteria we apply to gather the sample of headlines allow us to ensure that the sign of the innovation is stated in the headline (see Appendix A).[6] However, the news-based identification of the triggers implies that the

[6] In the previous version of the paper, we also attempted to obtain the signs from the yield movements themselves. However, as the yields of various maturities may not always co-move, this led to ambiguous results in some periods when the yield curve rotated. The approach with signs obtained from the headlines is, according to our observations, more robust.

magnitude of an innovation is not known, although it is to some extent possible to differentiate news discussing significant movements from news discussing only mild volatility. Therefore, for an innovation $x_{c,t}$ in category c, we know the prior for the time t and the sign, but not the absolute value of the magnitude of the innovation. We solve this problem using a combination of two model elements. First, we estimate the *magnitude of the innovation* in its absolute value within the Bayesian setup. We use a log-normal prior distribution for the absolute value of the magnitude with both mean and standard deviation equal to one. This implies that the mode of the distribution is also equal to one, i.e., the prior tends to place the magnitude of the innovations close to unit size if the data do not state otherwise. Second, by introducing the time-varying parameters $\boldsymbol{\beta_t}$ as defined above, we model the *impact of the innovations*. The intuition behind including both the *magnitude* and the *impact* variables lies in their different specifications and estimations. The time-varying impact variables $\boldsymbol{\beta_t}$ are estimated within the state-space setup using filtering and therefore have the capacity to show longer-term trends in the importance of innovations in various categories. In contrast, the mutually independent magnitudes of $x_{c,t}$ may be seen as certain "adjustments" of the innovations that help the model fit the naturally varying importance of unique events. Therefore, introducing the magnitude allows us to distinguish between the usual idiosyncratic volatility of yields related to individual events and longer-term trends in volatility and its causes.

We estimate the model using Bayesian updating, utilizing the Gibbs sampling procedure with the Metropolis Hastings step for sampling the location and magnitude of the innovations. The details on the estimation procedure are summarized in Appendix A. The prior distributions of the parameters other than innovation location and magnitude (the covariance matrices of measurement errors and of random disturbances in the time-varying parameter process) are set as standard in the literature; details are included in Appendix A. Since the Gibbs sampling algorithms for state-space models usually require a large number of iterations to converge, we set the number of burned iterations to 50,000, despite the relatively quick convergence of likelihood and stability of the results. We then save 5,000 iterations, which provides sufficient dimensions for evaluating the posterior probabilities. The results of the estimation comprise the posterior distribution of the location and the magnitude of the innovations $x_{c,t}$, the posterior distributions of the covariance matrices $\boldsymbol{Q}$ and $\boldsymbol{R}$ and the posterior distribution of the time-varying parameters (model states) $\boldsymbol{\beta_t}$.

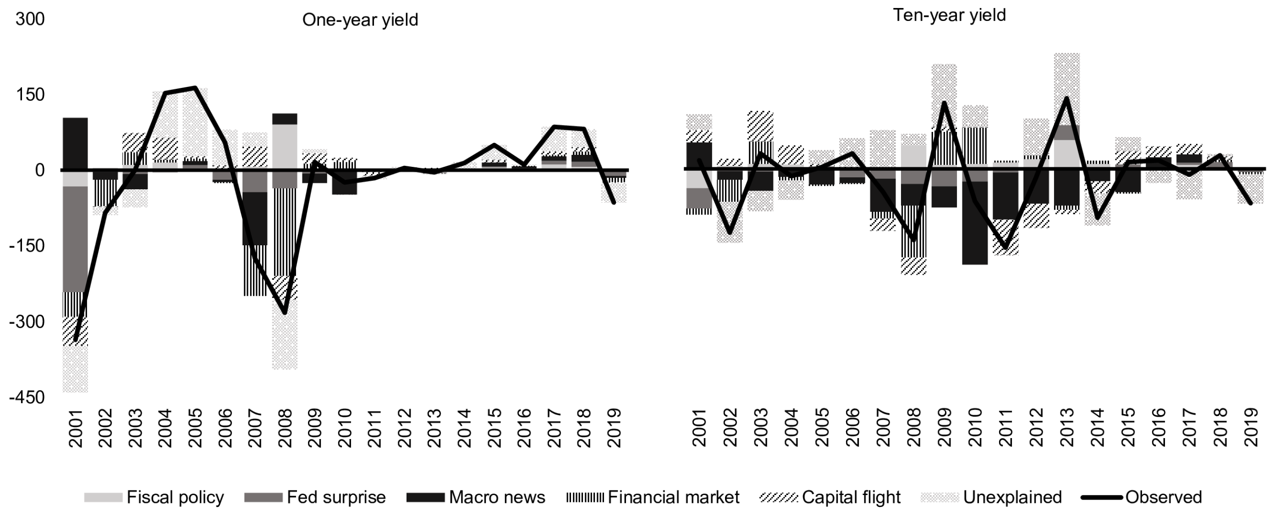
2.5 Empirical Results

After estimating the models, using the data as described in Section 2.3, we begin by describing the main results and discuss their implications. Thereafter, we provide further comments and outline the results for individual components of the model. At the end of this section, we also present the results of a counterfactual analysis that offers an additional perspective on the obtained results.

2.5.1 Main Results

The aim of the paper is to measure the importance of various categories of events when explaining the variability in U.S. Treasury yields. To do so, we compare the observed and model-implied daily changes in yields. The model-implied values are obtained from (2.4) by plugging in the posterior mean and selected quantiles for $\boldsymbol{\beta_t}$ and $x_{c,t}$. A separation of the model-implied changes into the contributions of individual innovation categories allows us to obtain a measure of the importance of the categories.

Figure 2.3: Annual Yield Movements and Their Decomposition (in bps)



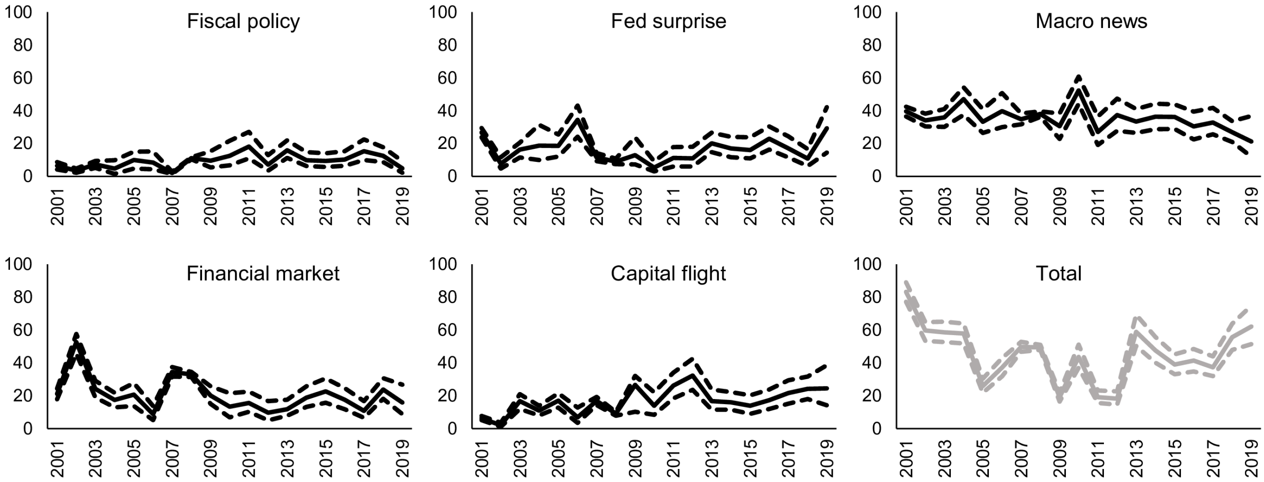
We show the results aggregated per year to emphasize the most important findings. The annual changes in yields are calculated as a sum of daily movements over each year. The mean posterior model-implied annual changes of one-year and ten-year yields are presented in Figure 2.3. The figure shows several important findings. First, we focus on the triggers related to the monetary policy response to crises. As the results show, the decline in short rates in 2001 was broadly triggered by a Fed announcement, whereas the 2008 rate decrease was expected from macroeconomic news and especially in relation to financial market events, i.e., before to Fed's reaction. Second, focusing on the differential transmission of the Great Recession into short- and long-term yields, we observe that the macroeconomic news triggered the response of short-term yields in 2007, whereas the longer Treasuries priced the macroeconomic conditions gradually between 2007 and 2015. This shows that the depth of the crisis and the extent of the monetary policy response, including quantitative easing, were initially underestimated – otherwise, the longer yields would have adjusted more quickly. Third, capital flight affected the yields mostly in the same direction as did the other categories of innovations, i.e., the flight to/from quality in periods of market uncertainty/optimism served as a multiplier of the other triggers. Finally, the extent of the unexplained movements is significant, although not dominant. This highlights possible further improvements in the news headlines sample (using body of news articles instead of mere headlines), which we see as an interesting challenge for future research. However, we do not consider this to be a fatal weakness of our model.[7]

The annual changes may lack a significant amount of information on intra-year movements that may compensate for each other. Therefore, we also calculate the absolute value of the daily movements, both observed and model-implied. The annual sums of the daily absolute movements attributed to each category of innovation, compared to the total model-implied absolute movements, are shown in Figure 2.4 (for the one-year Treasury yield), Figure 2.5 (for the ten-year Treasury yield) and Table 2.2.

As it is shown, the events captured by the macro news were historically the most important triggers of yield changes. However, their importance has decreased since the Great Recession in favor of capital flight events that gradually became the most important source of yield changes at the end of the period of analysis. The share of the total model-implied and observed historical variance (bottom-right panels of the figures) was highly volatile, between 20 and 80% of the observed variance (but less than 50% in the case of ten-year Treasury yields). This is mostly a consequence of the presence of less significant "technical" movements and corrections that may have driven the Treasuries market

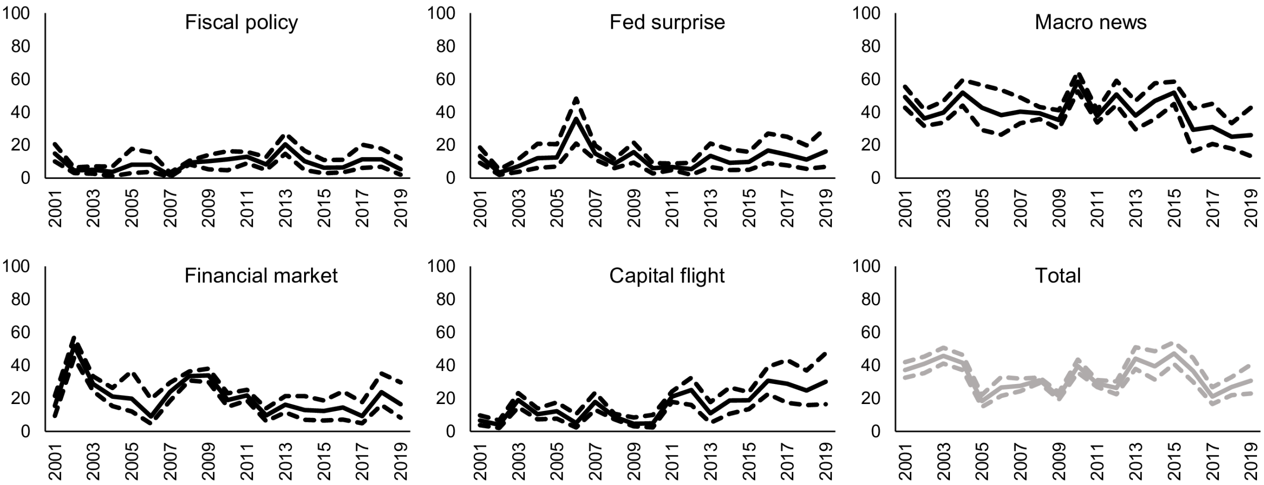
[7] See the discussion on the trade-off between the accuracy of the filtering and the in-sample fit in Section 2.3.

Figure 2.4: Shares of Annual Absolute Yield Movements, One Year (%)



Note that the shares of the five categories are calculated as an annual sum of absolute values of model-implied daily movements in the yield for the given category as a percentage share of the total annual sum of absolute values of model-implied daily movements. The share of the total absolute model-implied changes (bottom-right panel) is calculated as the percentage share of the observed annual sum of absolute values of movements in the yield. The dotted lines represent 10% and 90% credible intervals.

Figure 2.5: Shares of Annual Absolute Yield Movements, Ten Year (%)



See note at Figure 2.4 for details on the figure.

in periods lacking significant innovations and were therefore poorly captured by the news headlines. For the short-term yield, the decreased variance since 2009 (see Figure 2.2) in a low-yield environment may partially explain the limited robustness of the share of total explained variance.

The presented identified increase in the importance of capital flight events

Table 2.2: Relative Shares of Annual Absolute Yield Movements by Category (in %)

	Fiscal Policy		Fed surprise		Macro news		Fin. market		Capital flight	
	1Y	10Y	1Y	10Y	1Y	10Y	1Y	10Y	1Y	10Y
2001	6.45	14.91	26.72	13.57	39.61	49.38	21.10	15.48	6.26	6.66
2002	3.44	4.58	7.76	3.32	34.12	36.23	52.65	51.86	2.03	4.01
2003	7.29	5.03	16.31	7.24	35.91	39.86	24.21	28.78	16.73	19.09
2004	4.77	3.72	18.73	12.16	47.09	52.28	17.41	21.34	10.89	10.49
2005	9.95	8.47	18.57	13.15	33.19	44.75	20.69	20.78	16.97	12.84
2006	8.37	8.49	34.42	37.31	39.71	39.69	8.83	9.35	6.87	5.15
2007	2.07	1.74	11.51	15.03	34.76	40.85	34.49	24.23	16.80	18.15
2008	11.03	9.44	9.04	8.76	37.97	39.33	32.98	33.57	9.06	8.91
2009	9.54	10.34	12.99	15.78	30.53	35.29	20.18	34.00	26.66	4.60
2010	12.47	11.39	5.34	6.00	52.32	58.72	13.38	19.04	13.88	4.85
2011	18.14	12.89	11.17	6.69	26.97	37.60	15.57	21.79	26.13	21.04
2012	7.17	8.38	10.95	5.53	37.28	51.10	9.70	9.74	32.29	25.25
2013	15.90	20.69	20.05	13.68	33.35	38.20	11.85	16.34	16.78	11.09
2014	9.82	10.49	17.02	9.40	36.31	47.87	18.80	13.16	16.08	19.09
2015	9.36	6.31	16.04	9.97	36.19	52.27	22.66	12.51	13.85	18.94
2016	10.19	6.63	22.95	17.06	30.47	30.02	17.51	14.81	17.31	31.47
2017	15.33	12.03	17.03	15.01	32.78	32.67	10.77	9.79	21.66	30.50
2018	12.57	11.83	10.87	11.72	26.84	26.03	23.74	24.77	24.26	25.66
2019	4.84	5.63	29.26	17.14	21.23	27.66	15.87	17.54	24.42	32.03

Source: News Monitor at EIKON – Refinitiv, author's calculations.
Note that the median shares of the five categories are displayed. They are calculated as an annual sum of absolute values of model-implied daily yield movements for the given category as a percentage share of the total annual sum of absolute values of model-implied daily movements. Therefore, for each year and each maturity, the sum of the shares equals 100%.

represent important evidence in favour of the main hypothesis of the paper. Furthermore, it has implications for the discussion of the spanning hypothesis, i.e., whether the (macro) factors affecting the yields are perfectly spanned by the yield curve. The literature either rejecting (Joslin *et al.* 2014, for instance) or supporting (Bauer & Hamilton 2017, for instance) the spanning hypothesis mostly focuses on macroeconomic variables (see Section 2.2). Our results do not resolve this discussion but hint that the discussion should focus also on the non-macroeconomic factors as an important source of the variation in yields.

We further support our findings by a robustness check for the ten-year yield. We split the period of analysis into two sub-samples, separated by the Great financial crisis, and estimate the model for each sub-sample. The results are very close to the full-sample results (see Appendix A), which proves sufficient robustness of our conclusions. Certain differences appear in individual years (the importance of macro news has increased in favor of Fed surprise in 2006 and in favor of fiscal policy in 2013, for instance), but the main trends in the shares remain unchanged.

2.5.2 Discussion of the Estimated Parameters

To further understand the results, it is useful to display the elements forming the main results. These are (i) the posterior location of the innovations $x_{c,t}$, (ii) their posterior magnitude and (iii) the posterior distribution of the time-varying parameters. The figures accompanying the text below are included in Appendix A.

The posterior location of the innovations is shifted slightly towards later dates compared to the day when the news was published. The average difference over the full sample was 0.61 business days. We interpret this as indicating that the news is timely, i.e., the model estimation does not generally tend to shift the location into the past, which would be needed if the news were published with a delay. In contrast, the slightly forward-looking nature of the news can be seen as caused by the events that happened after markets closed and, therefore, the news was published before it was priced in on the next business day. The lagged posterior distribution of the innovation location after the news was published also signals a certain momentum in the response of the yields, either because the innovation itself was distributed over time or because the market responded with limited efficiency. The posterior distribution had a heavy upper tail in 2008 and 2011 (see Figure A.2), which signals certain momentum in the market response over periods with increased uncertainty (the U.S. subprime mortgage crisis and the eurozone debt crisis; see Table A.2).

The posterior distribution of the magnitude of innovations shows that in most years, the average magnitude of the innovations is less than that implied by the prior distribution (see Figure A.3).[8] The only exception is the year 2008, when the magnitude increased instead (see Figure A.4). The results thus show that the motivation for including the magnitude parameter was correct, as it allows the model to distinguish periods of increased volatility without the need to introduce a more complex model that would allow for stochastic volatility.

Finally, the values of the time-varying parameters $\beta_{c,t,f}$ – the sensitivity of the latent yield factors $F_{f,t}$ (the level, slope and curvature) to yield innovations $x_{c,t}$

[8] The prior log-normal(1,1) distribution has a mean of 4.48.

– show some longer-term trends in the impact of the innovations on the yields. As Figure A.5 shows, the sensitivity of the $F_{1,t}$ factor (the level, i.e., the yield component common for yields to all maturities) increased significantly for the Fed surprise category of events between 2008 and 2010, for macro news events between 2003 and 2006 and since 2010 and for capital flight events between 2011 and 2018. The results suggest that the yield curve as a whole had an increased sensitivity to innovations from the particular categories over these periods. The sensitivity of $F_{2,t}$ factor (the slope, i.e., the yield component with a decreasing weight for increasing maturity) was elevated for financial market events and fiscal policy events first during 2008 and, afterwards, between 2010 and 2015. Over 2008, the short-term rate reached a record low level, mostly following financial market news – the sensitivity of the slope factor especially to the financial market news is therefore justified. Between 2010 and 2015, the short-term rate remained at the low level with limited volatility. Therefore, we interpret the elevated sensitivity of the slope factor to the financial market news in the way that if there was volatility in the short rate over the period 2010–2015, it was linked predominantly to financial market causes.[9]

Note that we do not enforce nonnegativity of the time-varying parameters. The negative values may seem ambiguous, as we handle the sign of the innovation explicitly in the measurement equation by obtaining it directly from the headlines. The negative sign is a consequence of an imbalance between the dimension of the yield curve (a set of maturities) and the number of innovations (a single value for each innovation). Therefore, if different parts of the yield curve respond differently to the innovation (in either magnitude or sign), the negative value in the sensitivity of one of the latent factors allows the yield curve (or its movements) to take various shapes. The benefit of such an approach is the availability of information from the whole yield curve.

The detailed analysis represents additional evidence for the existence of a growing trend in the importance of capital flight events for the yield curve movements over the last decade. The time-varying parameter linking the capital flight innovations and the level of the yield curve is significantly positive after 2010, with two peaks in 2011 and 2016.

[9] We omit a discussion on the curvature factor, which allows us to fit the middle part of the yield curve, and its interpretation may not be straightforward.

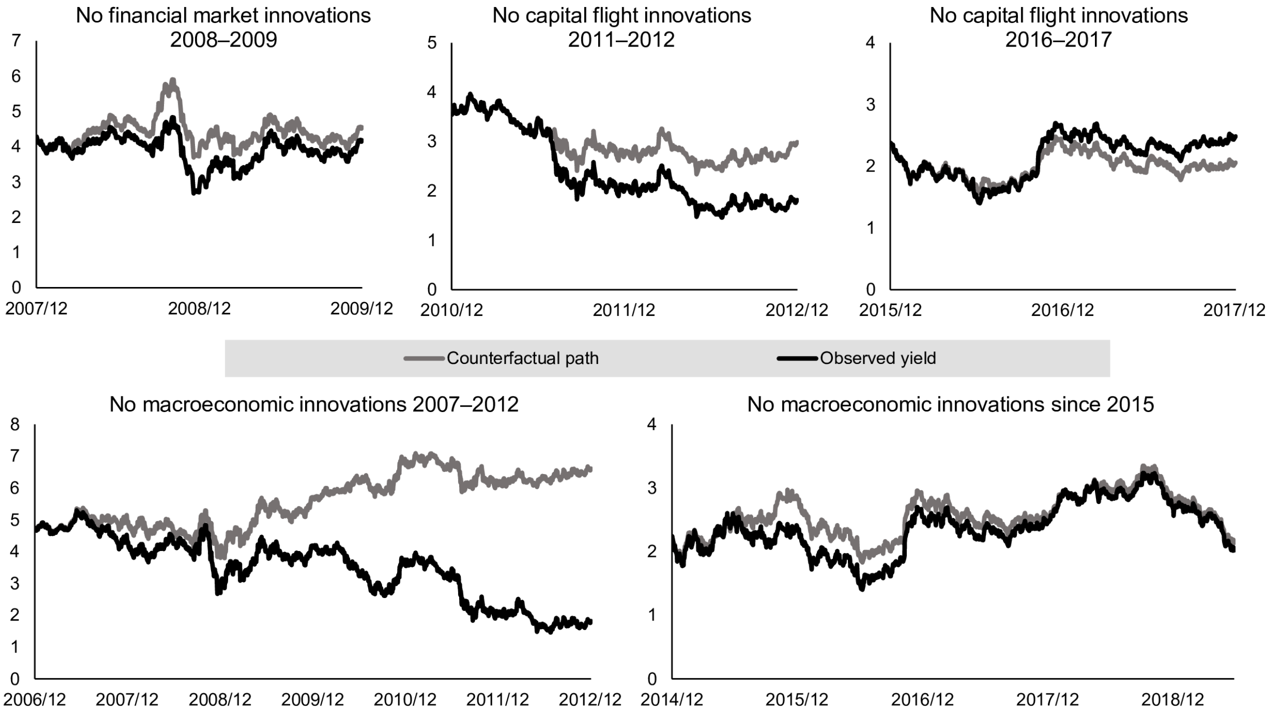
2.5.3 Counterfactual Analysis

To offer an additional view on the implications of our findings, we calculate counterfactual paths for the ten-year U.S. Treasury yield by switching off the innovations of individual categories over selected periods. These hypothetical paths could be considered naive since we do not assume interdependence among the innovations in our model. Analogous to the discussion in Section 2.4, we argue that the counterfactual paths are accurate as long as markets correctly foresee all impacts of the innovations and the transition of an innovation through the economy and into the yields is sufficiently fast. For example, if financial turmoil motivates investors to change their required yield to an extent reflecting not only the expected impact of the news on financial markets but also the impact on the future macroeconomic position and subsequent Fed decisions, then switching this innovation off allows us to accurately draw a “no turmoil” counterfactual path. Although the assumptions of efficient markets and perfect information are strong and generally not fully satisfied, we believe that the counterfactual paths we obtain have the capacity to at least roughly illustrate how the yields would evolve if certain events had not occurred.

The resulting paths are captured in Figure 2.6. The upper three panels display counterfactual paths of the ten-year yield if financial market or capital flight innovations were not present over the chosen subsamples: the 2008 financial crisis, the 2011 eurozone debt crisis and the events of 2016. Beginning with the former, the absence of negative financial market news during 2008 would keep the ten-year yield above the actual values. The decline in yields during the second half of 2008 would still be present, although of a lesser magnitude than in the case of the actual dynamics. On the other hand, the rebound in the yield during 2009 would be smaller, and therefore, the end of 2009 difference between the actual and hypothetical yield would be limited. This shows that the absence of financial turmoil would result in less volatility over the crisis period, although not a new trend in yields.

The decline in the yield since summer 2011, attributed in the news to a deepening eurozone crisis, would not be present if the capital flight events were turned off (see Figure 2.6, top-middle panel). The absence of the flight-to-safety behavior transferring capital from the eurozone to the U.S. would result in a U.S. yield 117 basis points above the actual value at the end of 2012. The absence of the Brexit referendum in June 2016 would similarly imply avoiding a minimum yield level of 1.40% from July 8, 2016, which would remain 16 basis points higher

Figure 2.6: Counterfactual Paths of Ten-Year Treasury Yield (in %)



Note that the counterfactual path is calculated as the median path over all posterior draws.

(see Figure 2.6, top-right panel). Nevertheless, the absence of news from this category would result in a lower yield later in 2016 and throughout 2017, which would mostly be attributed to the absence of a positive impact of the result of the 2016 U.S. presidential election on the yield.

We also display the hypothetical effect of an absence of macroeconomic innovations on the yield in the bottom part of Figure 2.6. First, focusing on the period 2007–2012, switching off macroeconomic news would imply a lesser downward trend in the yield over 2007–2008, a strong upward trend between 2009 and 2010 and stable yield over 2011–2012. The difference between the actual and counterfactual paths in scenario is substantial, which shows that the macroeconomic position was the dominant source of the downward trend in yields after 2006.

In contrast, the yield would remain mostly unchanged if the macroeconomic innovations were switched off beginning in 2015 (see Figure 2.6, bottom-right panel). The downward trend in yields in 2016 would be delayed, and the effect of the U.S. presidential election in 2016 would be smaller, but the end-of-period actual and hypothetical yields would be almost identical. Again, this particular result illustrates that the non-macroeconomic events were the core source of the variation in yields over the last decade.

Overall, the results illustrate the magnitude of the impact of events unrelated to the U.S. macroeconomic position on U.S. yields. International capital flight has proven to be an important source of yield variation since 2016. This finding has implications for U.S. monetary policy. The transition of Fed monetary policy adjustments into longer yields may face increasing challenges due to effects of additional yield factors outside the control of U.S. monetary policy. These challenges are relevant especially to the conventional monetary policy using the Fed funds rate. However, any unconventional monetary policy tool, except for the direct yield curve targeting, faces such challenges, albeit to a lesser extent.

2.6 Conclusion

The paper demonstrates the importance of events beyond the U.S. macroeconomic conditions for explaining recent movements in the U.S. Treasury yield curve. The analysis utilizes a Bayesian approach to identify the magnitude and location of innovations related to the stance of macroeconomy and monetary policy, portfolio allocation decisions and Treasury supply. Using a time-varying regression model, we obtain filtered estimates of the impact of innovations in each category on the yields. The results show that the events related to the U.S. macroeconomic news were the most important triggers of the yield curve movements over most of the period under analysis. However, the importance of non-macroeconomic events grew over the period. The events related to capital flight became the most important triggers of longer yield movements after 2016, explaining even more than one-third of the variation in longer yields in 2019. These effects were narratively obvious, particularly in relation to events including various phases of the eurozone debt crisis, the Brexit referendum, the U.S. election in 2016 or the trade tensions since 2017. Such results are in line with the discussion of a revival of Greenspan's conundrum due to non-macroeconomic factors, as discussed in Bauer (2017).

We consider the causes of the documented trend—the growth of the relative importance of non-macroeconomic events—to be complex. First, the proximity of the lower bound of yields, experienced over the last decade, naturally reduce the space for the Fed funds rate volatility. Therefore, the pass-through of shocks to U.S. macroeconomic conditions and, consequently, also of the response of the monetary policy to the yields could be limited. Second, and related, cause might be the abundance of global cheap funding and, simultaneously, a lack of local investment opportunities providing sufficient yield, that supported the cross-border capital flows due to the global search-for-yield behavior (Buch *et al.* 2014). Third, we argue that the actual importance and frequency of global non-macroeconomic events causing flight to safety increased over the last decade, in line with increased geo-political uncertainty and global political instability. Finally, ongoing longer-term trends in the globalization, strengthening and/or newly emerging cross-border contagion channels might be part of the explanation. Some of these views may be supported by the narrative evidence presented by Table 2.1 and Table A.2. A complex empirical evaluation of the causes of the documented trend themselves is, however, left for future research.

The framework presented in this paper also allows us to estimate counterfactual paths of yields. We show that whereas the absence of macroeconomic news would result in a slightly upward trend in the ten-year U.S. Treasury yield over the period 2007–2012, instead of the actual downward dynamics, it would not significantly alter the path of the yield after 2014. The absence of news related to capital flight would prevent the decline in yields over 2011 or in the days following the Brexit referendum. This further illustrates that the non-macroeconomic events became important when explaining yield dynamics.

The implications of the results are straightforward. From a monetary policy perspective, the monetary policy authority should not neglect external factors that may affect the transition of either conventional or unconventional monetary policy steps through the yield curve. Regarding yield curve modeling, the discussion of spanning hypothesis (and, in general, the model selection) could benefit from the presented results. Specifically, it can be expected that an inclusion of non-macroeconomic variables in macrofinance yield curve models could prove beneficial to capture and explain part of the variation in yields.

Chapter 3

Yield Curve Dynamics and Fiscal Policy Shocks

3.1 Introduction

What is the impact of government spending on the term structure of interest rates? The existing literature provides little guidance as it is either predominantly focused on studying implications of fiscal policy for the real economy or on the interactions between changes in bond prices and the real economy.[1] Empirical research studying directly the link between fiscal policy and the yield relies mainly on the least-squares estimates reduced to single bond maturity (see Evans & Marshall 2007, Laubach 2009 or Gale & Orszag 2003).

We bridge these literature streams and study the effect of government spending on the yield curve using a variety of VAR models. These model vary both in the way fiscal policy shocks are identified—either (i) identification within the VAR model using the actual spending figures in line with Blanchard & Perotti (2002), (ii) using a forward-looking approach to shock identification in the sense of Ramey (2011) or (iii) utilizing estimates from a DSGE model—and the way the yield curve enters these VAR models: as a single yield together with the Fed funds rate; or being represented by the level, the slope and the curvature of the yield curve; or in the form of yield curve factors from an up-to-date yield curve model by Bauer & Rudebusch (2020). Such a wide scale of model specifications allows

[1] Impact of fiscal policy for the real economy has been extensively covered in the literature on fiscal multipliers (see Christiano *et al.* 2011 for a survey). Research studying impact of bond prices for real economy is dominated by financial frictions literature, see Brunnermeier *et al.* (2012) for a survey.

us to describe the transmission of the government spending shocks into the yield curve in a robust way while focusing on effects of changing timing of the shocks. The ability of the affine term structure model to decompose the responses of the yields to the risk-neutral yield and the term premium also provides us a powerful tool to identify various channels that facilitate the transmission.

The complexity of our approach allows us to verify multiple findings from the literature, which mostly focuses on individual channels of a fiscal shock transmission into yields. Dai & Philippon (2005) point to the fact that government deficits can temporarily affect long term interest rates. The impact of changes in government expenditures received however less attention than government deficits and it has been believed that government spending has marginal impact on the yield curve (see, for instance, Evans & Marshall 2007). This is a surprising result as the textbook economic theory predicts that an exogenous increase in public spending should lead to a rise in aggregate demand (Baxter & King 1993) driving interest rates up (Fisher & Turnovsky 1992). In addition, if the rise in expenditures is financed by debt the bond supply, literature documents the positive relationship between supply of outstanding government bonds and interest rates (see Krishnamurthy & Vissing-Jorgensen 2007 for literature review).

Ramey (2011) is among the first to forcefully document in empirical study the importance of fiscal foresight in the response of the economy to rises in public expenditures.[2] The fiscal foresight literature (see Leeper *et al.* 2012) complements the "news" literature (Beaudry & Portier 2006 and Barsky & Sims 2011) which posits that business cycles arise on the basis of expectations of future fundamentals rather than on the impact of shock. The importance of news shocks for yield curve has been established in Kurmann & Otrok (2013); they show that it is the news about future total factor productivity which explains more than 50% of the unpredictable movements in the slope of the yield curve. However,

[2]Gale & Orszag (2003) provide extensive literature review on how the timing of fiscal policy in case of deficit and debt matters for the response of the yields. For instance, Barth *et al.* (1991) surveys 42 studies and finds: from 19 studies with projected deficits 13 have positive, 5 mixed effects, 1 no effect. Gale & Orszag (2003) redo Barth *et al.* (1991) and find: 18 studies have positive effect, 6 mixed effects, 19 not significant or negative. Similar conclusion found by Mankiw (2000). Often cited papers by Evans (1987) or Plosser (1982) find no effect. Ardagna *et al.* (2007) use both a simple static estimation and a vector autoregression model for a panel of countries and show that an increase in the primary government deficit increases the long-term yields. However, in the case of an increase of the government debt, the yields are affected only for the above-averagely indebted countries. Laubach (2009) shows the upward effect of fiscal expansion on the long-term yields by comparing the budget deficit forecasts with the long-horizon forward rates.

the effect of news about government spending on the yield curve has not been studied in the literature. Yet intuitively many fiscal policy measures are known well in advance. The lags in decision and implementation can be demonstrated by many examples. Trump's fiscal package to boost infrastructure spending has been debated since he won the election. Obamacare[3] was discussed for more than a year before coming into force a the implementation was only gradual. Ramey (2011) lists other examples related to defense spending as the aftermath of 9/11 or Soviet invasion of Afghanistan, where the rise in defense spending was anticipated in advance.

Being partially motivated by the fiscal foresight literature, we compare the response of the yield curve to fiscal policy shocks when using various methods to identify the shocks. First, we use the canonical shocks identified in line with Blanchard & Perotti (2002) from the actual government spending data. In this case, we confirm the positive effect of an increase in government spending and therefore of a deficit on yields from Gale & Orszag (2003) and others. We also demonstrate the importance of distinguishing between the response of the risk-neutral yields that are responsible for the overall increase in yields and the additional effect of term premium that may diminish the effects for longer yields. Second, we confirm these findings also by estimating the shocks within a DSGE model and subsequently using them in our VAR framework.

Third, we obtain the spending shocks from the changes in projections of government spending by CBO (2020) and therefore identify them well before they enter the spending data. In this case, the initial response of the yields is opposite, i.e., they drop temporarily after an expansionary fiscal policy shock. We attribute this drop to a cautious response of economic agents due to an uncertainty related to the expected future fiscal policy shock. We provide additional view on the importance of the fiscal foresight by focusing also on fiscal policy uncertainty (FPU) instead of the government spending and demonstrate that the degree of perceived uncertainty related to expected future fiscal policy shocks is crucial for the way how these shocks propagate into yields. Such finding on the importance of the timing of the shocks is broadly in line with the contribution of Ramey (2011).

By this set of findings, we are able to describe the full dynamics of propagation of government spending shocks to the Treasury yield curve. The initially formed expectations about future fiscal policy steps may induce uncertainty that causes

[3] Patient Protection and Affordable Care Act.

yields to drop temporarily, either due to a real economic response of the economic agents or due to a flight-to-quality behavior. After several quarters, when the fiscal policy is actually realized, the initial drop is exchanged for in increase, in line with the broad literature. Depending on the nature of the shock and the response of the term premia, the yields may eventually gradually decrease to the initial levels or remain elevated over a longer period.

The rest of the paper is organized as follows. Section 3.2 further describes our empirical framework, the motivation to use a set of models and the channels that are expected to be crucial for the shock transmission. Section 3.3 introduces the Treasury yield curve and the way it is incorporated into the modelling framework, with special attention given to the description of the model by Bauer & Rudebusch (2020) and its results. Sections 3.4–3.6 present results of VAR models in the form of impulse-responses, while each of these sections uses a single approach to fiscal policy shock identification. Finally, Section 3.7 summarized the results and relates them to the literature and Section 3.8 concludes.

3.2 Empirical Approach

We use multiple model specifications to evaluate linkages between the U.S. fiscal policy shocks and the U.S. Treasury yield curve. Three different approaches are followed to specify the fiscal policy shocks, and, simultaneously, three different ways of representing the yield curve are utilized. Therefore, nine model versions in total are evaluated to provide a wide view on multiple channel through which the fiscal policy shocks affect Treasury yields (Table 3.1).

The relations between the fiscal policy and Treasury yield curve are captured by VAR models. The models use three blocks of variables. The **first block** includes the Fed funds rate and yields or yield curve factors, depending on the specific model version. These variables facilitate both observing the response of the yield curve to the fiscal policy shocks and controlling for the changes in the monetary policy. We use several levels of complexity of yield curve modeling, including either an individual yield time series into a VAR model ("YLD" specification), the yield factors representing the level, the slope and the curvature of the yield curve ("LSC" specification) or yield latent factors obtained from an no-arbitrage affine term structure model by Bauer & Rudebusch (2020) ("AFF" specification). The various yield curve modeling approaches, motivation

Table 3.1: Model Versions

Fiscal shock specification	**Yield curve representation** Individual yields (YLD)	Level, slope and curvature (LSC)	Affine Term Structure Model Factors (AFF)
Identification within structural VAR model (SVAR)	SVAR-YLD (see 3.4.1)	SVAR-LSC (see 3.4.2)	SVAR-AFF (see 3.4.3)
Identification using narrative apprach (NARR)	NARR-YLD (see 3.5.1)	NARR-LSC (see 3.5.2)	NARR-AFF (see 3.5.3)
Structural shocks from DSGE model (DSGE)	DSGE-YLD (see 3.6.1)	DSGE-LSC (see 3.6.2)	DSGE-AFF (see 3.6.3)

for using them and the properties of some of the model outputs, before entering VAR models, are described in Section 3.3.

As as **second building block**, one or more fiscal policy variables are used. Using multiple approaches to fiscal policy shock identification provides us a complex view on the interaction and, simultaneously, relate our results to multiple streams of the fiscal policy literature. The approaches include (1) the baseline fiscal policy shock identification using structural VAR, similarly to Blanchard & Perotti (2002) ("SVAR" specification); (2) a narrative-based approach that attempts to identify the shocks well before they enter the fiscal figures by observing changes in projections by Congressional Budget Office ("NARR" specification); and (3) an estimation of structural shocks using a DSGE model ("DSGE" specification). Each of Sections 3.4–3.6 in this paper describes in detail one of these approaches and shows the results.

We prefer to work with parsimonious VAR models throughout the paper. Therefore, when using the affine term structure and the DSGE model, we take a "two-step" approach. In case of the affine model, this means that we first estimate the model separately and the use its outputs in a VAR framework to measure the linkages between the yield curve and the fiscal policy shocks. It would be also possible to follow a "one-step" approach and incorporate the fiscal policy variables into the affine model directly, as did Dai & Philippon (2005). This would, however, reduce the comparability of the affine model as well as its possible robustness, given the specificities of estimating the yield curve model with unobserved stochastic trend (Bauer & Rudebusch 2020). Additionally, the challenges related to “spanning hypotheses would need to be solved Joslin *et al.* (2014). Moreover, the “two-step” approach does not provide significantly different results, as discussed in De Pooter *et al.* (2010) and Joslin *et al.* (2011). Similar arguments apply to the DSGE model: while it is compelling to show the relations of the fiscal policy shocks identified within a DSGE model and the yield curve directly, the comparability of such results and various other shock identification approaches would be limited: it would be difficult to distinguish model-based differences and “pure” identification-based differences. Also, this would require specifying and estimating multiple DSGE model version which would further extend the analysis beyond a reasonable scope and leave little space for shock identification beyond DSGE approach (see the discussion in Section 3.6).

The use of multiple approach to specification of fiscal policy shocks is motivated by understanding various channels of their propagation into the real economic, financial markets and, finally, the Treasury yields. To avoid over-parametrization of the models, we consider using a set of various models as a more robust approach, compared to using a single large-scale model that would try to include all relevant information. The specific transmission channels will be emphasized in the discussion parts of the individual sections below. Providing their summary here, we consider the most important channels to be (i) the *real channel* (evaluated by Blanchard & Perotti 2002 or Ramey 2011, among others): the real response of economic agents to the fiscal policy shock on the aggregate demand (consumption, investments), which propagates to the real activity, the unemployment and inflation, and finally also the monetary policy response with impact on yields; (ii) the *financial market sentiment channel (partially commented on by Bauer 2017)*: the flight to or from Treasuries representing the safe haven or an insurance vehicle in line with the theoretical model of Horvath *et al.* 2017; (iii) the *Treasury supply channel*, discussed in Gale & Orszag (2003), Dai & Philippon (2005), Ardagna *et al.* (2007) and Laubach (2009), among others, and closely related to the hypothesis of the crowding-out effect[4], that captures the effect of changes in government budget that needs to be financed on the financial market, i.e., increased government indebtedness, moving the Treasury supply and hence affecting the yields; and (iv) *debt sustainability channel* comprising

[4]See Spencer & Yohe (1970) for an important contribution and Moretti *et al.* 2019 for a recent reference.

changes in Treasury risk premia due to changes in government indebtedness and overall uncertainty related to government financing.[5]

Third, business cycle variables represented by real GDP growth and annual rate of inflation are included. These are important control variables with respect to both the yield curve movements (Ang & Piazzesi 2003) and the correct fiscal policy shock identification.

We use quarterly data between 1985/Q2 and 2020/Q1. The use of quarterly data provides sufficient number of observed periods and, simultaneously, facilitates modeling of longer-term transitions.[6] The beginning of the sample is constrained by the availability of the data (especially fiscal projections data and uncertainty indices, see Section 3.4. Beginning of the sample in mid-1980s also ensures that the sample starts after the Fed monetary policy using monetary aggregates targeting was mostly abandoned.[7]

3.3 Yield Curve Data and Modeling

We use zero-coupon Treasury yields from Gurkaynak & Wright (2007). We include maturities 1–15 years in our sample, which we further extend by 3-month and 6-month Treasury bill yields from Fed (2019). Since we use fiscal and control macroeconomic variables observed at a quarterly frequency, we gather the end-of-quarter yields. We present the evolution of U.S. government bond yields over the selected period in Figure 3.1. In this period, the yield curve was mostly upward-sloping, with few exceptions prior to the 1990, 2001 and 2008 crises. Since the end of 2008, the lower bound proximity has apparently been

[5] The names of the transmission channels are specific for this paper to help emphasize the core interactions that the empirical part shows. However, they follow the most common explanations of the transmissions as found in the literature—see the references at each of the channel. A more general economic theories and concepts could be also mapped to the channels. Using the IS-LM model as an example, the expansionary government spending shock would move the IS curve up and to the right, and thus increase both the interest rate as the unmoved LM curve will imply scarcity of funds and the crowding-out effects (our *Treasury supply channel*). As the product also increases above the potential in this model, the inflation increases as well and the monetary authority responds by moving the LM curve up and to the left, which increases the interest rate further (this would fall into our *real channel*).

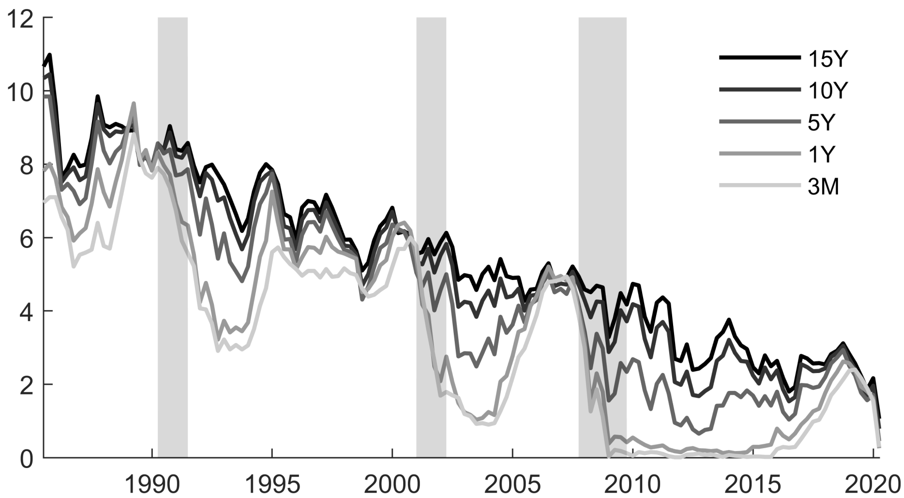
[6] The latter would require VAR models with large number lags and therefore might result in less robust results in case monthly data were used instead.

[7] Including the monetary aggregate targeting period would could provide biased results. The models do not assume time-varying volatility of yields; however, the period of increased inflation and monetary aggregate targeting could imply structurally different yield volatility therefore result in bias if not controlled for. Since 1985, we consider the inflation to be at the sufficiently low levels and monetary targeting policy to be largely deemphasized (Mishkin 2001).

effective, as the short end of the yield curve fluctuated around the zero level with a limited volatility. At the end of 2015, the lift-off of the short yields began to take place, whereas the long end of the yield curve gradually decreased over the whole period.

Lower bound proximity poses threat of biased results of the affine term structure model, which we use below. However, the model of Bauer & Rudebusch (2020) allows to treat the yields close to the lower bound in certain periods as missing—therefore, the zero lower bound has only a limited impact on the validity of the term structure model, compared to the case of the Gaussian stationary models (see Krippner 2015 for discussion).

Figure 3.1: Treasury Yields (in %)



Note: The shaded areas show the NBER-defined crises.

We demonstrate the linkages of fiscal policy shocks to yields using multiple representations of the yields. As a starting point, we include five-year Treasury yield together with the Fed funds rate into the models. This approach provides the first view on the implication of various approaches to the fiscal policy shocks identifications for their linkages with yields.

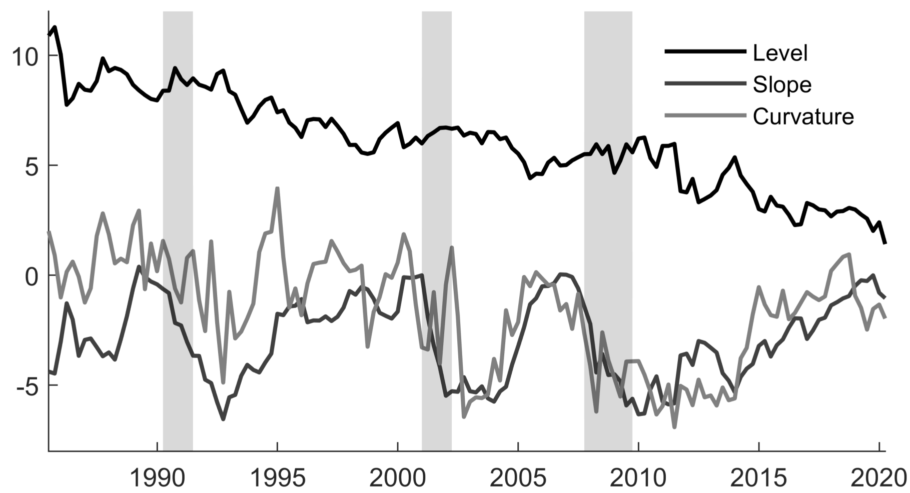
To generalize results for the whole yield curve, we replace the single yield by the level, the slope and the curvature of the yield curve, obtained using Nelson & Siegel (1987) functional representation of the yield curve:

$$y_t(\tau) = L_t + S_t \frac{1 - e^{-\lambda\tau}}{\lambda\tau} + C_t \left(\frac{1 - e^{-\lambda\tau}}{\lambda\tau} - e^{-\lambda\tau} \right) , \tag{3.1}$$

where $y_t(\tau)$ is a yield with a time to maturity τ in time t, L_t, S_t and C_t are the level, the slope and the curvature of the yield curve and λ is a scalar parameter. L_t, S_t and C_t can be obtained individually for each period t by considering them as unknown parameters and fitting the functional form to the given term structure of interest rates $y_t(\tau)$ via OLS.[8] In the case of this approach, we omit the Fed funds rate from the model to simplify the model and avoid multicollinearity. The slope factor reflects the fluctuations on the short end of the yield curve, and, therefore, provides sufficient information about the short rate movements.

Figure 3.2 presents the estimated L_t, S_t and C_t of yields. The level of the yield curve is declining gradually together with the longer yields. The slope of the yield curve mirrors the way the short rate was fluctuating around the level. Finally, the curvature of the yield curve is more volatile than the level and the lope and loosely follows combined developments of both the level and the slope, allowing for improved fit in the middle of the yield curve.

Figure 3.2: Yield level, slope and curvature



Note: The shaded areas show the NBER-defined crises.

As a most complex representation of the yield curve, we estimate an affine no-arbitrage term structure model and use obtained yield factors to represent

[8]The λ parameter is considered to be fixed for the whole sample. We set its value by finding numerically the optimal values minimizing the difference between the observed and fitted yields. The optimal value 0.0409 is lower than the value 0.0609 applied in Diebold & Li (2006), meaning that our yield curves have the maximum loading curvature related to a lower maturity.

the yield curve. The added value of using the term structure model is its ability to decompose yields, and also yield responses to fiscal policy shocks, to the risk-neutral expectations and the risk premium. Such decomposition provides further insight into the nature of the model-implied response of yields to shocks.

We use the affine term structure model of Bauer & Rudebusch (2020). The model incorporates time-varying trends in the longer yields, which is suitable for modeling the downward trend in U.S. Treasury yields over the last four decades and allows us to decompose the yields into the risk-neutral expectations and the risk premium without a bias. The core element of the model is the process which the three yield curve factors F_t follow under the data-generating (real-world) measure $\mathcal{P}$. The use of three factors is common in the term structure literature, given the importance of the first three principal components of yields as documented by Litterman & Scheinkman (1991). The term structure literature usually considers the $\mathcal{P}$-measure process to be of a stationary vector VAR(1) process. The model by Bauer & Rudebusch (2020) differs by assuming the process for F_t is given, apart from the three stationary factors $\widetilde{F}_t$, also by a single stochastic trend τ_t following a random walk process (Bauer & Rudebusch 2020):

$$F_t = \bar{F} + \gamma\tau_t + \widetilde{F}_t, \quad \tau_t = \tau_{t-1} + u_{\tau,t} \quad \widetilde{F}_t = \Phi\widetilde{F}_{t-1} + u_{F,t}, \tag{3.2}$$

where γ is a 3-vector determining the way how the stochastic trend affects single yield factors, $u_{\tau,t} \sim N\left(0, \sigma_\tau^2\right)$ and $u_{F,t} \sim N\left(0, \Omega\right)$ are assumed to be i.i.d. and mutually orthogonal and Φ is a VAR(1) loadings matrix assumed to ensure stationarity of $\widetilde{F}_t$ process, i.e., with eigenvalues less than ones.

The model can be written in a state-space form, with the transition equation defined by (3.2). To obtain the measurement equation, the factor process first needs to be specified also under the risk-neutral $\mathcal{Q}$-measure. Following Bauer & Rudebusch (2020), the $\mathcal{Q}$-process is assumed to be stationary, which ensures that the yields do not explode with increasing bond maturity:

$$F_t = \bar{F}^Q + \Phi^Q F_{t-1} + u_{F^Q,t}, \tag{3.3}$$

where Φ^Q is a VAR(1) loadings matrix assumed to ensure stationarity of F_t process under $\mathcal{Q}$-measure and $u_{F^Q,t} \sim N\left(0, \Omega\right)$ are assumed to be i.i.d.

The affine class of no-arbitrage term structure model is defined by assuming an affine mapping of the short rate on the yield factors, i.e., $i_t = \delta_0 + \delta_1' F_t$. This, together with (3.3), determines the $\mathcal{Q}$-path for i_t, which under the risk-neutral measure directly determines the observed yields, which are affine function of the yield factors with parameter matrices A and B:[9]:

$$Y_t = A + BF_t + u_{y,t}, \tag{3.4}$$

where $u_{y,t} \sim N(0, R)$ is assumed to be i.i.d. measurement noise. (3.4) represents the measurement equation of the model.

To obtain unique values of the yield factors, several restrictions are imposed (see Bauer & Rudebusch 2020 for detailed discussion and further reference). First, to ensure the observed yields imply unique F_t, restrictions on the parameters in (3.3) are imposed.[10] The model by Bauer & Rudebusch 2020 uses the restrictions by Joslin *et al.* (2011), which is one of the most popular approaches in the literature, given its parsimony: (3.3) is defined by a single scalar and three eigenvalues of Φ^Q, only. Second, as the three factors F_t are driven by four underlying factors (three $\widetilde{F}_t$ and one τ_t), restrictions are needed to identify unique process for τ_t. Bauer & Rudebusch (2020) use restrictions in both $\bar{F}$ and γ vectors and also set $\tau_t = i_t^* = \delta_0 + \delta_1' F_t^*$, where $F_t^* = \bar{F} + \gamma\tau_t$ are the expected long-run mean values of the factors and the stochastic trend τ_t is viewed as the long-run mean short rate.[11]

To summarize, the state-space form of the model is defined by (3.4) and (3.2) with restrictions imposed as described above. Bauer & Rudebusch (2020) discuss two approaches to estimate the model. First, when τ_t is considered as observed by using relevant proxy, the model can be the estimated effectively separately for measurement and transition equations, using maximum likelihood estimation and ordinary least squares, respectively, following the common approach by Joslin *et al.* (2011). Alternatively, a Bayesian estimation using Metropolis Hastings procedure can be used when τ_t is required to keep unobserved and estimate within the model. In this case, a set of priors on the dynamics of τ_t is required instead.

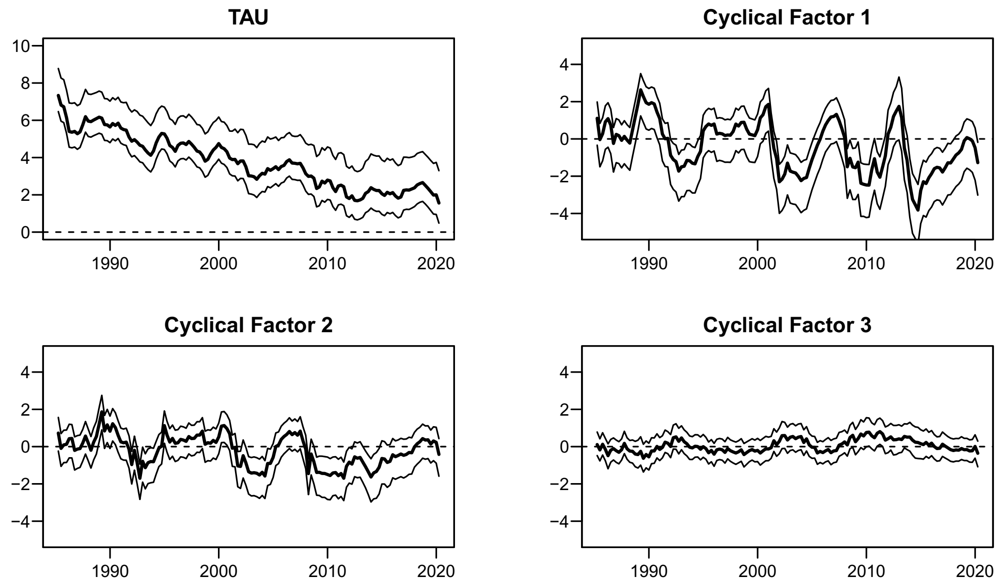
[9]See Ang & Piazzesi (2003), Joslin *et al.* (2011) and online appendix of Bauer & Rudebusch (2020) for derivation of the matrices A and B. The derivation is non-trivial and the matrices themselves are defined iteratively for increasing maturities and therefore are not further described in this paper. Referring to Ang & Piazzesi (2003) for providing more detail on the matrices is common in the term structure literature.

[10]Without the restrictions, a "rotation" would be possible, given the affine nature of the model. That means, that given the observed yields, an infinite number of yield factors could be inferred.

[11]Note that the long-run means are time-varying, which is the key advantage of this model.

We follow the latter method, because it avoids the use of a proxy which could strongly influence the results of the paper. The Bayesian approach also allows us to handle the period of the lower bound proximity by treating part of the sample (the shorter end of the yield curve for the given periods) as missing observations. The priors as well as the design of Metropolis Hastings procedure were take directly from Bauer & Rudebusch (2020). The estimated model parameters are summarized in Section B.1. The resulting factors (τ_t and $\widetilde{F}_t$) are displayed in Figure 3.3, the three yield factors F_t would be obtained through (3.2). The factor dynamics confirm that they were estimated in line with the aim of the model. τ_t factor is responsible for overall decrease in yields over the last decades, whereas the cyclical factors $\widetilde{F}_t$ define the way how the yields of various maturities fluctuated around the trend.

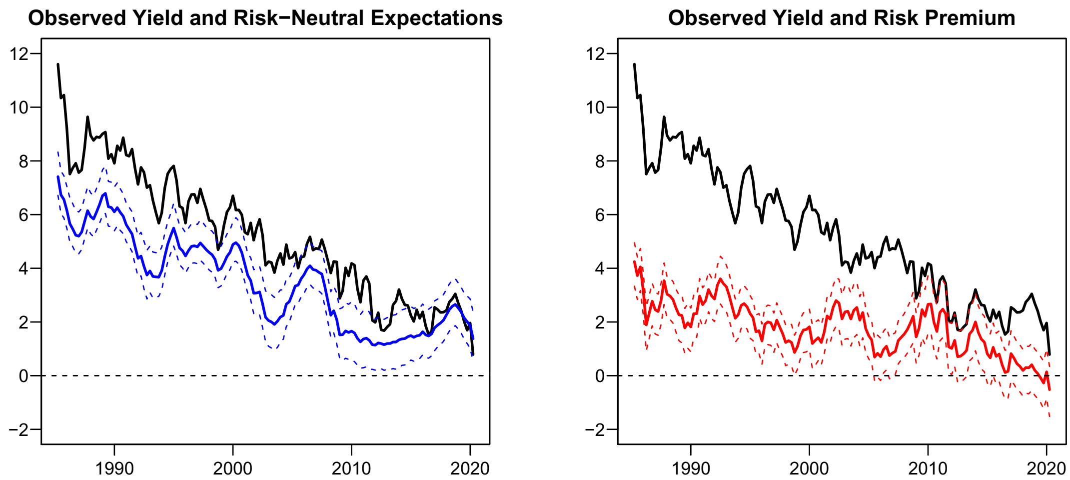
Figure 3.3: Yield Factors τ_t and $\widetilde{F}_t$



Note: The narrow lines display the 90% credible intervals. The values of factors are multiplied by 100 to better illustrate their relation to yields in percentage terms.

Further, the resulting loadings matrix B show that the difference between short and long yields (which includes also the term premium) is mostly reflected by the third yield factor $F_{3,t}$, whose cyclicality is driven by $\widetilde{F}_{3,t}$. As Figure 3.3 shows (bottom-right panel), this factor grew in value in during early 1990s, around 2001 and between 2007–2010. This clearly shows counter-cyclicality of the term premia implied by the model. The counter-cyclicality is an important property of the term premia (Bauer *et al.* 2014) and confirms that the model is correctly specified and estimated. This is also evaluated explicitly by decomposing the yields to the risk-neutral expectations and the term premia[12] (see Figure 3.4). The longer-term decline in yields is attributed mostly to a drop in risk-neutral yields, which is in line with the literature (Bauer *et al.* 2014). The overall behavior of term premia estimated in our model is in line with results of Bauer & Rudebusch (2020) and also similar studies which control for small sample bias and use the affine term structure models (Christensen & Rudebusch 2016, for example).

Figure 3.4: Ten-Year Yield Components (in %)



Note: The dashed lines display the 90% credible intervals.

3.4 Fiscal Policy Shocks Identification Using Structural VAR

The first approach to the identification of the U.S. fiscal policy shocks follows the work of Blanchard & Perotti (2002). The fiscal policy shocks are identified based on data on government net taxes and spending within a VAR model, using restrictions on the contemporary relations among the fiscal policy variables and

[12]With certain simplification, the risk-neutral expectations component is calculated as a mean expected future short rate, which is obtained from expected path of the yield factors under the $\mathcal{P}$-measure via (3.2). The term premium is the difference between the yield and its risk-neutral expectations.

real GDP. The model of Blanchard & Perotti (2002) can be written as

$$Y_t = A(L)Y_{t-1} + U_t \ , \tag{3.5}$$

where Y_t consists of real U.S. GDP, net taxes (taxes less transfers) and government spending, all express in terms per capita and using quarterly frequency. $A(L)$ denotes a lag polynomial. U_t gathers cross-corelated reduced-form residuals. Blanchard & Perotti (2002) impose restrictions on the relations among the reduced-form residuals and the structural shocks so that the model is identified in line with observed evidence. The model is estimated using quarterly dependence, i.e., four separate models are estimated for single quarters.

We extend the model to include also the yields or the yield factors and also provide some further adjustments in order to obtain interpretation useful for our purposes. We use GDP, quarterly net taxes and government spending all in year-over-year growth rates adjusted for inflation. Such dynamic transformation aligns our results with similar results from the term structure literature which predominantly uses macro-variables in their growth rates (see De Pooter *et al.* 2010 for overview). Also, in our case, using quarterly dependence and estimating four separate VAR models would provide weak results in terms of their robustness, as the extended model includes more parameters to be estimated against only limited number of observations. The use of year-over-year growth rates solves this issue by incorporating seasonality instead of using quarterly dependence. Our extended model includes additional variables: annual inflation rate and variables representing the yields. The inclusion of inflation is crucial to control for significant part of variation in yields.

We identify the model similarly to Blanchard & Perotti (2002), with adjustments reflecting our additional variables and the need to link them to the original ones. The reduced-form residuals written in the form of their combinations and the structural shocks:

$$\begin{aligned}
\text{net taxes:} \quad & t_t = a_1 x_t + e_t^t \ , \\
\text{government spending:} \quad & g_t = b_1 x_t + e_t^g \ , \\
\text{GDP growth:} \quad & x_t = c_1 t_t + c_2 g_t + e_t^x \ , \\
\text{price inflation:} \quad & p_t = d_1 t_t + d_2 x_t + e_t^p \ , \\
\text{yields and rates:} \quad & \text{depending on the approach to include yields,}
\end{aligned}$$

where e_t^* denotes the structural shocks. We differ from Blanchard & Perotti (2002) by several ways in the first three equations. First, we do not consider contemporary dependency of reduced-form residuals for taxes on structural shocks to spending and vice versa, given the claim by Blanchard & Perotti (2002) that their correlation is sufficiently small.[13] Second, we release the assumption that $b_1 = 0$, given the experience on the swift supportive reaction of the fiscal policy on economic negative developments during the Great Recession.[14] Instead, we impose the restriction on $c_2 = 1$, which is close to the Blanchard & Perotti (2002) result and is plausible due to the fact that the spending is part of the aggregate demand identity. It allows us to adjust the GDP growth identification equation to a private product growth: $x_t - g_t = c_1 t_t + e_t^x$, i.e., an innovation in GDP is contemporary linked only to the private product. To finalize the identification, we use the calibrated value for $a_1 = 2.08$ similarly as used in Blanchard & Perotti (2002).

The data on the government spending used within this approach to the identification of shocks are shown in Figure 3.5, the top-left panel. The data were obtained from Government Current Receipts and Expenditures tables from BEA (2020). The contemporary government spending for each quarter is calculated as a sum of government consumption expenditures, net interest payments and net investment expenditures.[15] As noted above, we specify the variable as year-over-year growth rate in the quarterly spending, where the annual growth rate helps to ensure that the seasonality pattern of government figures does not affect the results significantly. The data show an increase of government spending during 2008–2009 in particular, in the relation to the Global Financial Crisis breakout.

The remaining data are obtained as follows. The net taxes are obtained from BEA (2020) as well as a current taxes less transfers, while the inflation the real GDP and the Fed funds rate were obtained from FRED (2019), all being transformed again as year-over-year growth rates (more precisely the log-

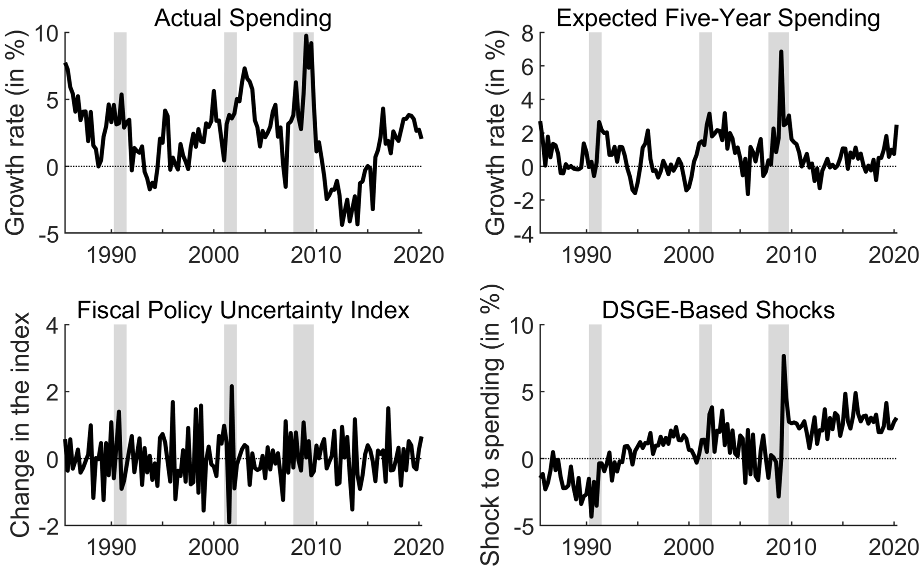
[13]More precisely, Blanchard & Perotti (2002) document that models with dependency of t_t on e_t^g and with dependency of g_t on e_t^t provide similar results.

[14]Economic Stimulus Act (2008); American Recovery and Reinvestment Act (2009).

[15]Using also net investment expenditures means that we consider the government spending in the wide context, i.e., not only the current expenditures. The expenditures related to net investments were added to the series so that our subsequent discussion on the possible effect of the risk premia and the Treasury supply side channel accounts for the whole amount of funds needed to be financed through the Treasuries. However, the expenditures related to net investments made only 4.9% of the total expenditures over the period under analysis. Therefore, we consider this adjustment to minor, to complete the picture while not changing the interpretation of the variable.

differences) of quarterly figures. The yield used in the model is as described in Section 3.3.

Figure 3.5: Government Spending Variables for Various Models



Note: The shaded areas show the NBER-defined crises.

3.4.1 Single-Yield Model (SVAR-YLD)

The first model version involves the Fed funds rate and a five-year Treasury yield as the representatives of the yields. We consider the monetary policy to react contemporaneously to innovations in GDP growth and inflation. The yield, which is a financial market variable, reacts contemporaneously to all other variables, whereas we put its reaction to the fiscal policy as a reaction to the innovation in the contemporary budget $(t_t - g_t)$. Therefore, the model identification is completed by the two equations:

$$\begin{aligned} \text{Fed funds rate:} \quad & f_t = e_1 x_t + e_2 p_t + e_t^f \ , \\ \text{five-year yield:} \quad & y_t = f_1(t_t - g_t) + f_2 * x_t + f_3 * p_t + f_4 f_t + e_t^y \ . \end{aligned}$$

We estimate the VAR model using OLS to obtain the reduced form shocks and series of regressions to obtain the shock identification parameters. Similarly to Blanchard & Perotti (2002), we use instruments by replacing the t_t by e_t^t in the GDP growth residual regression to obtain unbiased estimated of c_1 and then by replacing x_t by e_t^x in the spending residual regression to obtain b_1.

The lag of four quarters was chosen for the model. This lag seems to be close to the optimal, from the information criteria perspective, and yet does not imply too large model that would bring a risk of over-parametrization. See Section B.2 for visualisation of the information criteria for various lags—We consider Hannan-Quinn Information Criterion and Schwarz Information Criterion to be the most accurate, given the size of the sample and following the discussion in Ivanov & Kilian (2005). Both these criteria support 4–8 lags as the preferred choice, with the minimum for six lags. To keep the model parsimonious and avoid over-parametrization, we, however, use four lags as the final choice. We also tried to recalculate some of the results with six lags and they were not materially different. For the other models in this paper, the information criteria provided roughly similar results, i.e., favouring rather larger lags, but with the criteria values four lags being sufficiently close to the larger lags. Therefore, to make the results comparable and simplify the calculations, we used four lags throughout the paper.

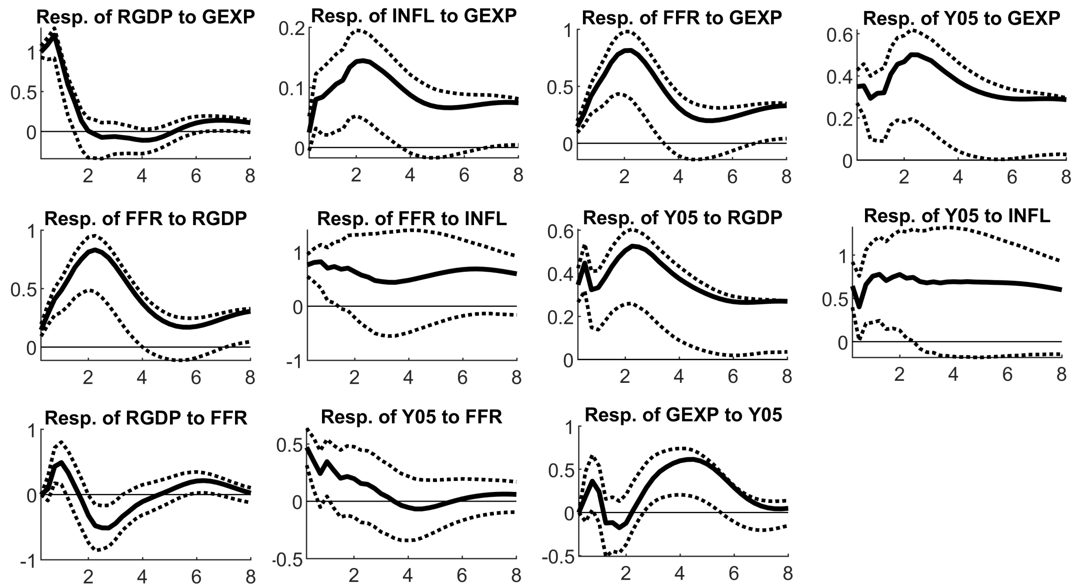
The results of the model are displayed in the form of selected impulse-responses in Figure 3.6.[16]. The impulses are set as an increase in a growth rate, the Fed funds rate or a yield by one percentage point, responses are also measured in percentage points. The dashed lines around the responses display 68% confidence bands obtained by bootstrapping.[17] The x-axis denotes years, i.e., the responses are calculated on a 32-quarter horizon.

The results demonstrate strong positive effect of a positive shock to government spending to both macroeconomic variables (GDP and inflation) as well as to the short rate and the yield (see the first row of Figure 3.6). The latter is directly given by the effect of economic growth on the yield curve (see the second row of Figure 3.6), i.e., the transmission from the government spending into the yields can be at a large extent attributed to the positive effect of the spending shock to GDP and inflation and hence the *real channel* of the transmission (see

[16]Given the number of models in the paper (and the need to generate two sets of impulse-responses for some models, both for the yield factors and for the yield), we do not display the full map of impulse-responses in the paper. They are, however, available with the authors upon request. For this reason, we also do not discuss further the effects of a shocks to government income, which is used in SVAR model specification only for the identification purposes and is not present in the other model specifications

[17]Using the asymptotic normality, the 68% level roughly represents single standard deviation confidence band, which is common in the literature to measure the effects of the fiscal policy – see, for example, Ramey (2011).

Figure 3.6: Impulse-responses in SVAR-YLD model (selected)



Note: The impulses are set as an increase in a growth rate or a yield by one percentage point, responses are also measured in percentage points. The x-axis denotes years. The dashed lines display the 68% confidence bands. RGDP=real GDP growth rate, GEXP=growth rate in government expenditures, INFL=annual rate of inflation, FFR=Fed funds rate, Y05=five-year Treasury yield.

Section 3.2). Apart from these observations, the model provides plausible results in overall—GDP decreases with some delay after a positive shock to the Fed funds rate, pass-through from the Fed funds rate shock to the five-year yield is less than proportionate and the government expenditures (including interest payment on government debt) increase after a positive shock to the yields. Naturally, the results of this model provide neither full information about the various impact on various parts of the yield curve nor insight into the behavior of yield risk premia. Such questions are answered using the other two methods of including the yield curve into the VAR model. In overall, after some generalization, it can be still concluded that an exogenous increase in government spending, if identified using structural VAR, results in an increase in yields largely due to positive effect of spending shock on the real economy (the *real channel*).

3.4.2 Level, Slope and Curvature Model (SVAR-LSC)

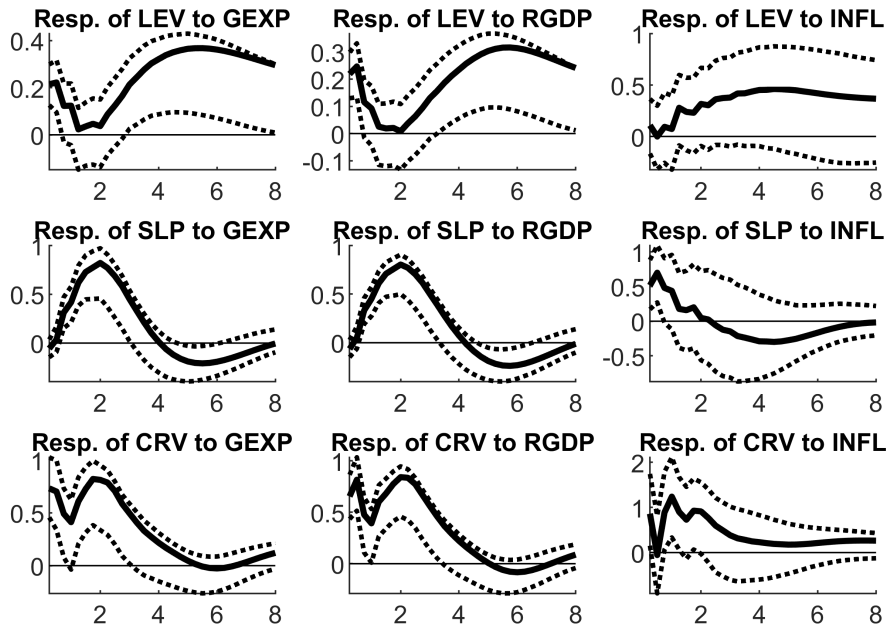
The similar model is obtained by including the level, the slope and the curvature yield curve factors instead of the Fed funds rate and the five-year yield into the model. Regarding model identification, we keep the original four equations and add identifying restrictions on the three yield curve factors. We assume that the level reduced-form residuals depend contemporaneously on the shocks to budget (similarly to the five-year yield in the previous model), GDP and inflation. The slope reduced-form residuals are linked to GDP, inflation and the level—the level dependence is motivated by the definition of level and slope.[18] Finally, the curvature, which may be difficult to interpret, is set as to be dependent on all other variables.

$$\begin{aligned}
\text{the level:} \quad & l_t = e_1\left(t_t - g_t\right) + e_2 x_t + e_3 p_t + e_t^l \ , \\
\text{the slope:} \quad & s_t = f_1 x_t + f_2 p_t + f_2 l_t + e_t^s \ , \\
\text{the curvature:} \quad & ct = g_1 t_t + g_2 g_t + g_3 x_t + g_4 p_t + g_5 l_t + g_6 s_t \ .
\end{aligned}$$

The results of the model are roughly similar to the previous case. GDP and inflation react positively to an increase in government spending, implying the government spending presents an expansionary shock. This propagates further into the level, the slope and the curvature of the yield curve (Figure 3.7) which determine also the responses of yields (Figure 3.8). The propagation is gradual over the response horizon. First, the level of the yield curve increases, whereas the slope and the curvature partially compensate this increase on the short and medium maturities. After several quarters, the slope and the curvature increase instead. We read this as an expected or realized response of the monetary policy and therefore the short rate to the economic growth (or vice versa in case of a negative initial shock). Finally, further in the propagation, the level increases once again and relatively persistently, whereas the short end of the yield curve is partially suppressed. That means that the longer yields do not drop back, unlike the short yields, in case of an expansionary shock. We argue that a plausible interpretation of this movement is the effect of an increase in the bond risk premia due to increased indebtedness (the *debt sustainability channel*). Such hypothesis is further evaluated below using the affine term structure model.

[18] For example, in case the long end of the yield curve decreases, but the short yields remain the same, the level of the yield curve drops whereas the slope increases (note that the level variable is common to all maturities). The dependence of slope shocks to the level shocks allows for correctly measuring the responses with respect to such events - the slope is viewed as providing an "extra" information about the short yields beyond the level.

Figure 3.7: Impulse-responses in SVAR-LSC model (selected, yield factors)



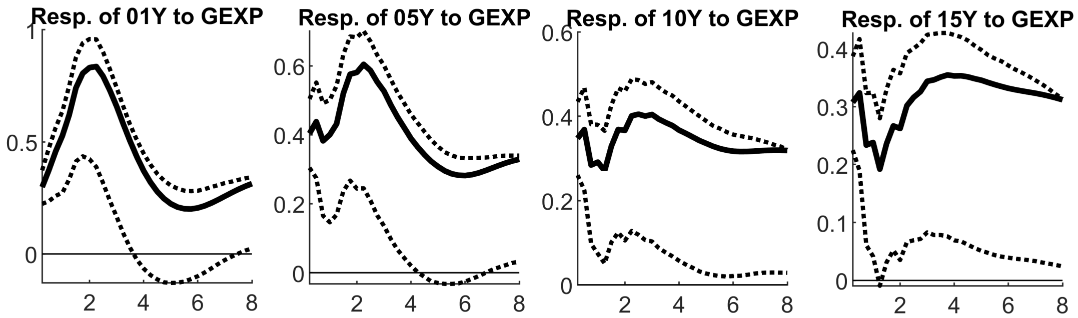
Note: The impulses are set as an increase in a growth rate by one percentage point, responses are measured in factor units. The x-axis denotes years. The dashed lines display the 68% confidence bands. RGDP=real GDP growth rate, GEXP=growth rate in government expenditures, INFL=annual rate of inflation, LEV=the level, SLP=the slope, CRV=the curvature.

3.4.3 Affine Term Structure Model (SVAR-AFF)

In the AFF model specification, the affine model stochastic trend τ_t and the three stochastic factors $\widetilde{F}_t$ enter the VAR model to represent the yield curve. After the impulse-responses are calculated, the responses in these factors are translated to responses in the three yield factors F_t through (3.2) and the yield responses are obtained from (3.4). We account for the affine model parameter uncertainty, and therefore, we use results from individual simulations obtained from the Metropolis Hasting algorithm when estimating the affine model to inter the VAR analysis (both for the yield factors and parameter estimates). This implies that the resulting impulse responses display credible intervals rather than confidence bands.

As described in Section 3.3, the affine model is used also for decomposing the responses to the risk-neutral expectations and the term premium. As Figure 3.9 shows, the main response of yields is similar to the case of the previous model specifications (see Figure 3.8 for comparison). Therefore, focusing specifically on

Figure 3.8: Impulse-responses in SVAR-LSC model (selected, yields)

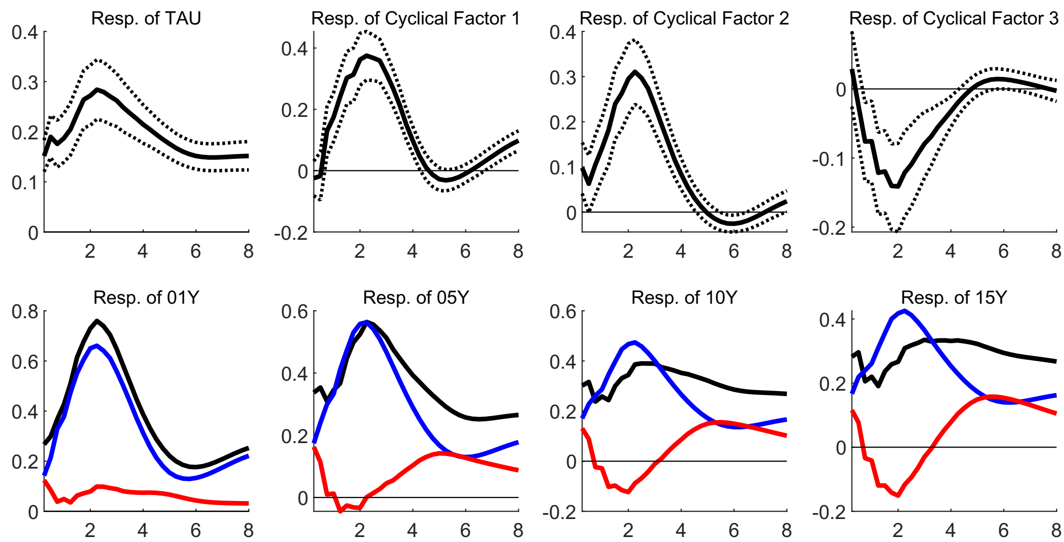


Note: The impulses are set as an increase in a growth rate or a yield by one percentage point, responses are also measured in percentage points. The x-axis denotes years. The dashed lines display the 68% confidence bands. GEXP=growth rate in government expenditures, xxY=xx-year Treasury yield.

the response of the components, the increase of yields after the initial spending shock is driven by an increase in the risk-neutral expectations. This implies that the *real channel* of the shock propagation is crucial: a positive government spending shock increases aggregate demand, which overall tends to increase interest rate environment due to the expected future monetary policy reaction to a shift in the business conditions and the inflation. The risk-neutral expectations can also increase due to the *Treasury supply channel* that would increase the interest rates due to a shift in the bond supply. However, the response in the risk-neutral yields is largest for the short yields, which signals that this channel is less relevant, given the additional bond supply is predominantly related to medium or long maturities.

An increase in the term premium was used as a possible explanation of persistence of the response of longer yields in the case of SVAR-LSC model. The decomposition confirms such view: for the longer yields in particular, the term premium first increases, then decreases to initial level or even below, and finally increases again. While our modelling approach lacks the possibility of explicit attribution of term premium volatility to various investor behavior, it can be intuitively argued that (i) the initial temporary increase in the term premium can be linked to the flight-from-quality behavior as the positive spending shock is viewed as an overall support for the economy and therefore risk-on sentiment prevails (*financial market sentiment channel*), (ii) the secondary drop in the term premium, representing further gradual shifts through the (*financial market sentiment channel*) due to a gradually diminishing initially positive effects of the policy shock, may be viewed as a signal of a medium-term need of economic agents to "hedge" against a possible delayed increased uncertainty related to possibly overheated economy, while (iii) the final longer-term increase in the term premium may be explained by an actual perceived riskiness of the Treasuries due to fiscal policy uncertainty and increased Government indebtedness (*debt sustainability channel*). Regardless to the explanation and channel attribution, the important finding is that the term premium explains significant part of the response especially for the delayed part of the response.

Figure 3.9: Responses in SVAR-AFF model to government spending impulse (selected)



Note: The yield response (black) is decomposed to the response of the risk-neutral yield (blue) and the response of the term premium (red) at the bottom panels. The impulses are set as an increase in a growth rate, responses are measured in factor units or yield percentage points. The x-axis denotes years. The dashed lines at the upper panel display the 68% credible intervals. xxY=xx-year Treasury yield.

3.5 Narrative Approach

The second approach to identification of fiscal policy shocks is largely motivated by the results of Ramey (2011), who shows that the Blanchard & Perotti (2002) identification is not be able to identify the shocks in the moment they are announced, as the time of announcement often precedes the time the shock appears in the fiscal figures by several quarters. Therefore, Ramey (2011) argues that the identification of the shocks needs to be done based on narrative evidence and uses news-based approach to obtain such shocks.

We follow this motivation but develop own approach to identification of narrative shocks. Unlike Ramey (2011), we do not restrict the shocks to a defense spending only, mostly due to a relatively scarce resulting sample of such shocks that would not be suitable for explaining the volatility in Treasury yields.[19] Instead, we use the regularly published projections of government outlays by the Congressional Budget Office (CBO). These projections are published since 1983 on at-least bi-annual basis. We gather projections five years ahead from each published report (CBO 2020), discount them using contemporary Treasury yield curve and sum them over the five years to obtain time series representing the present-value of five-year-forward expected government spending. These series represent our narrative-based forward-looking government spending variable. The fiscal projections from the Congressional Budget Office were similarly used by Laubach & Williams (2003), who focused on measuring the relationship between the change in projected deficit and long-horizon forecasts of government yields. The obtained time series of the expected government spending are shown in Figure 3.5, the top-right panel. The peak in 2008–2009 is present also in the case of the forward-looking series; however, the dynamics of the series is otherwise quite different to the actual government spending series (compare with the top-left panel).

We employ year-over-year growth rate of this expected five-year spending, adjusted for inflation, within a VAR model. The non-governmental data are identical to those used by the previous SVAR model specifications, depending on the specific model version (YLD, LSC or AFF). We use Choleski decomposition of the covariance matrix to identify the model. To obtain correct identification of the fiscal policy shocks, we order the expected spending behind GDP growth and inflation to control for the changes in the fiscal outlooks that were induced by changes in macroeconomic conditions (Kilian & Lütkepohl 2017). Therefore, we interpret the structural shocks to the expected spending variable as the macro-unrelated fiscal policy shocks. We order the variables representing the yield curve at the end of the VAR vector, in order for these variables to be contemporaneously

[19] Using defense spending data by Ramey (2011) is motivated by the fact that this category of spending may be seen as the most "exogenous", i.e., the changes in this category are driven by factors beyond the business cycle. The sample period in this paper is shorter then in the case of Ramey (2011) (see the discussion Section 3.2 for explanation). Therefore, replicating Ramey (2011) identification approach would provide too small number of narrative-based defense spending shocks and the results would not be robust. Therefore, we use the aggregate spending data instead. We ensure that the changes in government spending induced by business cycle shocks are correctly controlled for by ordering the spending variable behind the macroeconomic variables in the VAR model, as described below.

affected by shocks to macroeconomic and fiscal variables, similarly to the SVAR identification approach above.

3.5.1 Single-Yield Model (NARR-YLD)

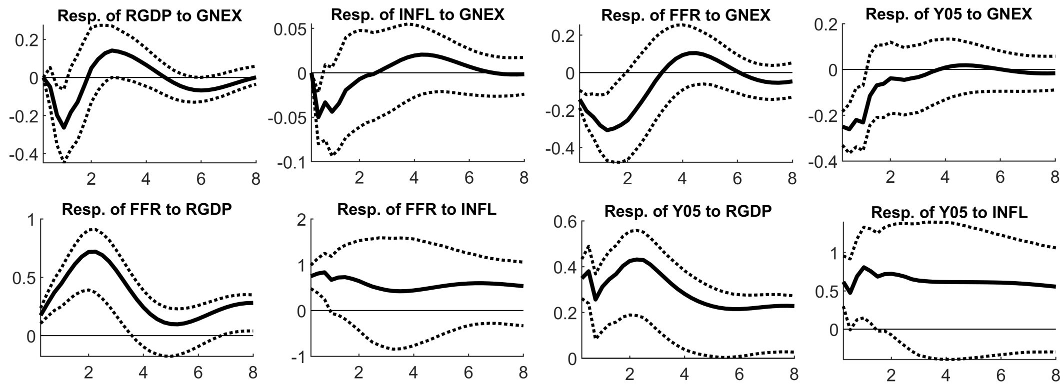
Similarly to the case of previous fiscal shock identification, yield curve is included into the VAR with narrative fiscal shocks either as a single yield (NARR-YLD model), as the level, the slope the curvature (NARR-LSC model) or as latent factors from the no-arbitrage affine term structure model (NARR-AFF model). Starting with the NARR-YLD model, its identification proceeds as described above, i.e., the VAR variables are ordered as follows: GDP growth, inflation rate, narrative government spending. The VAR vector is completed by the Fed funds rate and the five-year yield ordered at the end.

The results of the NARR-YLD model are displayed in Figure 3.10. The Fed funds rate and the yield respond positively to an increase in GDP growth and inflation similarly to the case of previous results (Figure 3.10, second row). A shock into the expected government spending, however, initially pushes the GDP growth and partially also the inflation rate down, and the growth restores with a certain delay (Figure 3.10, top-left chart). We consider this as an evidence of a cautious response of the economic agents to the announced spending, whereas the positive effect of spending shock on the aggregate demand applies with the delay after the government spending is realized. In line with the temporary economic slowdown after a positive spending shock, the yields initially drop as well through the *real channel* (Figure 3.10, top-right chart).

Such results are very close to the intuition offered by Ramey (2011), who demonstrates a drop in consumption after a positive spending shock (opposite to the evidence by Blanchard & Perotti 2002), once narrative approach helps to identify the shock before they appear in the governmental figures. We provide the same evidence on the response of yields. Both our results and the findings of Ramey (2011) are in line with Ricardian equivalence (Barro 1974), which suggests that economic agents will increase savings after an expansionary fiscal policy shock, which will drive both the consumption and the yields downward.

We, however, admit that the transmission of such shock is complex, including the expected monetary policy response, bond market investors' response to the expectations about future new emissions of Treasuries (the *Treasury supply channel*), as well as the possible either cautious or over-optimistic behavior of the economic agents. Depending on which of these channels prevails at various

Figure 3.10: Impulse-responses in NARR-YLD model (selected)

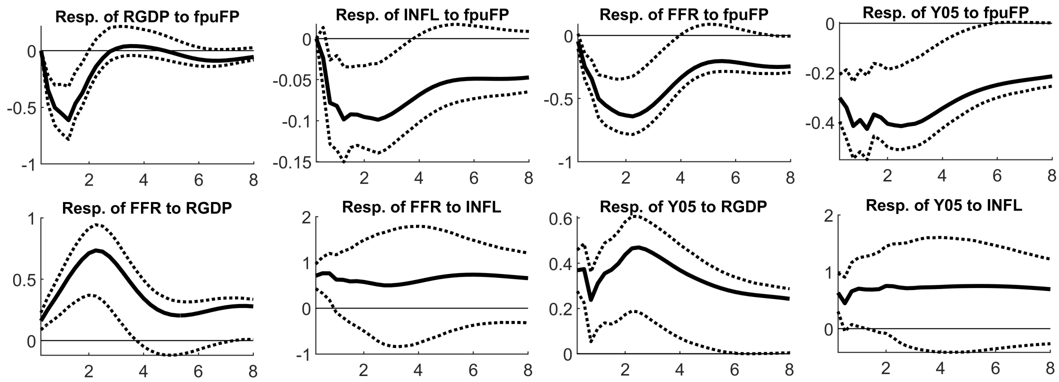


Note: The impulses are set as an increase in a growth rate by one percentage point, responses are also measured in percentage points. The x-axis denotes years. The dashed lines display the 68% confidence bands. RGDP=real GDP growth rate, GNEX=growth rate in the five-year projected government expenditures, INFL=annual rate of inflation, FFR=Fed funds rate, Y05=five-year Treasury yield.

maturities and response horizons, yields may increase or decrease. In particular, once an announcement of future government spending improves expectations of agents about the future economic prospects, the effect might be opposite, i.e., growth in both the consumption and the yields. For example, Bauer (2017) claims that the case when an anticipated fiscal stimulus improved agents' expectation about future economic situations and therefore drove yields upwards was observed after the 2016 presidential election.

We claim that the nature of the response, and the reason why our results suggest a drop in yields after the positive shock to expected government spending, are related to the perceived change in uncertainty of economic agents after the shock. To support this hypothesis, we estimate a model identical to NARR-YLD, only with the expected government spending variable replaced by the change in FPU index obtained from Baker *et al.* (2016) (see Figure 3.5, the bottom-left panel). The results are surprisingly close to the results of the NARR-YLD model (see Figure 3.11). The drops in the GDP growth, inflation and the yields are even more significant and persistent in case of a positive shock to FPU, compared to a positive expected spending shock. We consider this as a strong evidence showing that the drop following a positive expected spending shock is mostly caused by the uncertainty related to the shock and therefore cautious response of economic agents.[20] The additional factors and transmission channels may partially compensate for the effect of uncertainty, but either in on average lesser extent (positive expectations, growth in bond risk premia, etc.) or with a delay (the positive economic effect after the spending is realized, change in Treasury supply due to a need to finance the deficit[21])—these effects will be evaluated using the NARR-LSC and NARR-AFF models.

Figure 3.11: Impulse-responses in NARR-YLD model with FPU (selected)



Note: The impulses are set as an increase in a growth rate one percentage point, responses are also measured in percentage points. The x-axis denotes years. The dashed lines display the 68% confidence bands. RGDP=real GDP growth rate, fpuFP=growth rate in the FPU index, INFL=annual rate of inflation, FFR=Fed funds rate, Y05=five-year Treasury yield.

3.5.2 Level, Slope and Curvature Model (NARR-LSC)

We again further adjust the NARR-YLD model by replacing the Fed funds rate and the yield by the level, the slope and the curvature of the yield curve, ordered still at the end of the VAR vector. This allows us to generalize the aforementioned implications of narrative shocks to expected government spending for responses of the whole yield curve.

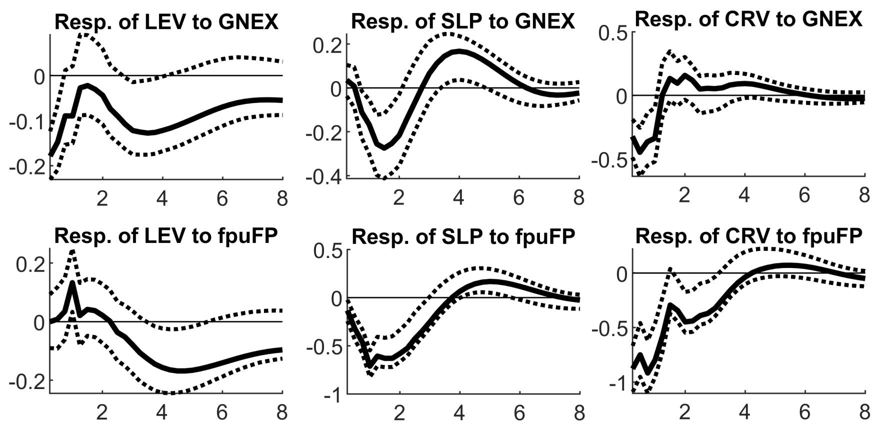
The positive response of the level, the slope and the curvature of the yield curve to an accelerated growth in GDP and partially also in inflation, only with

[20]We see two possible main transmission channels of the cautious response of agents. First, the economic consequences of the cautious behavior may imply overall economic slowdown, need for expansionary monetary policy and therefore also a drop in the Fed funds rate and in yields. Second, the uncertainty may trigger demand for the U.S. Treasuries as a safe haven asset, suppressing their yields and thus representing a transmission through the financial market. Disentangling the contribution of each of the effects is outlined in the subsection below that explicitly attributes the response to the changes in risk-neutral expectations (predominantly the economic channel) and the term premium (the financial market channel).

[21]Gale & Orszag (2003), among others, often mention the positive effect of increased government indebtedness on the yields.

various delays since the initial shock, is still present in the model. The difference from the SVAR-LSC model lies in the response to the government spending variable (Figure 3.12, top panels). We interpret the drop in level and temporary drop in slope (exchanged for a growth after some time) equivalently to the case of NARR-YLD model as caused by the cautious response of agents, which is present in the results thanks to the identification of the spending shocks ahead of their appearance in the fiscal figures. And equivalently to the NARR-YLD model, the importance of the effect of the uncertainty is also largely confirmed by the use of FPU index instead of the expected government spending variable (Figure 3.12, bottom panels). In this case, the level initially seems to increase slightly, which however only compensates the larger drop in the curvature, as will be obvious below when displaying the yield responses.

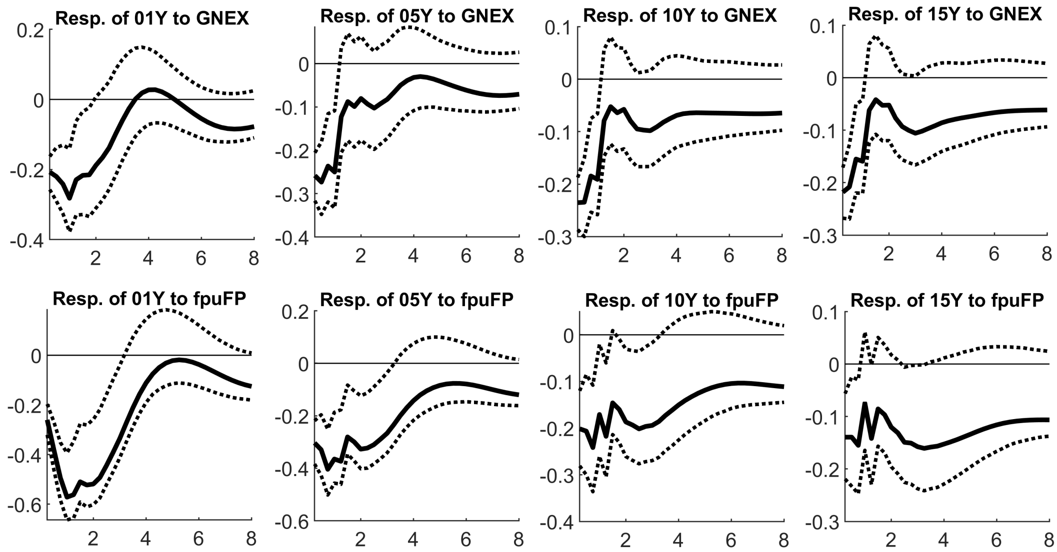
Figure 3.12: Impulse-responses in NARR-LSC model (selected, yield factors)



Note: The impulses are set as an increase in a growth rate, responses are measured in factor values. The x-axis denotes years. The dashed lines display the 68% confidence bands. GNEX=growth rate in the five-year projected government expenditures, fpuFP=growth rate in the FPU index, LEV=the level, SLP=the slope, CRV=the curvature.

The translation of the response of the level, the slope and the curvature to the response of yields is displayed in Figure 3.13. The initial drop in the level following a positive expected spending shock implies decrease in yields across all maturities. The immediate adjustment in yield may be interpreted in the light of the *financial market sentiment channel*, i.e., flight to quality, and the *real channel* via a growth in expectations about future monetary policy loosening given the adverse economic effects of the uncertainty. The economic response is reflected by the drop in the slope after several periods, i.e., an additional relative decrease in the short yields. This implies that the gradual return of the one-year is delayed, compared to the longer yields (Figure 3.13). Afterwards, the slope turns positive instead, however, the level still remains below the initial value. The yields therefore do not exceed their initial values over the whole response horizon. That shows that when correctly identified the for the initial negative effect of government uncertainty on the yields, the possible delayed positive effect of yields is not sufficient to rise the yields, unlike the case of the shock identification using the structural VAR model. The NARR-LSC model, compared to the NARR-YLD model, more emphasizes that the interaction among the initial drop across all yields and the delayed volatility in the short yields. In the case the FPU variable is used instead, the drop in longer yields is even longer-term (Figure 3.13, bottom panels).

Figure 3.13: Impulse-responses in NARR-LSC model (selected, yields)

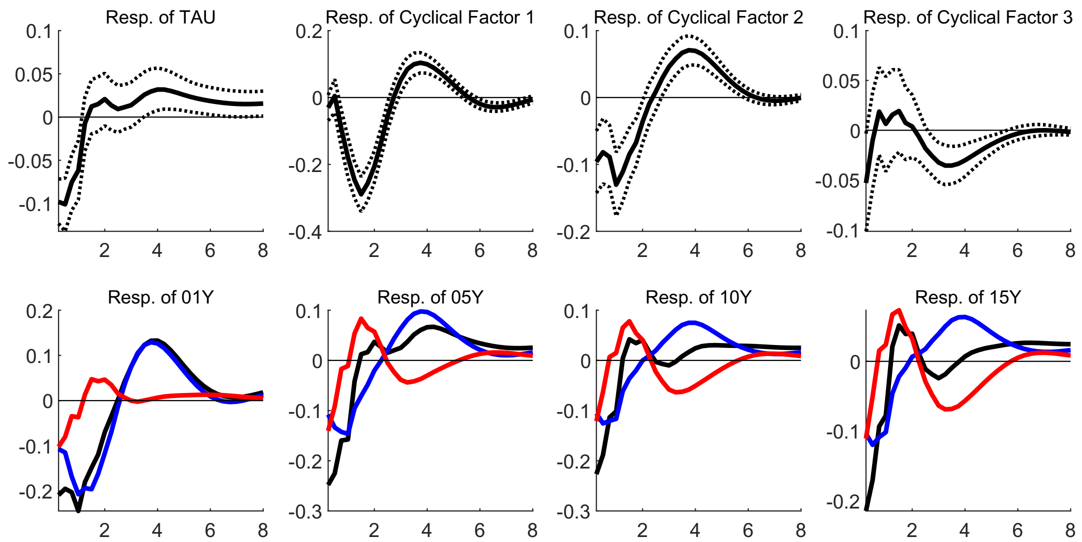


Note: The impulses are set as an increase in a growth rate by one percentage point, responses are also measured in percentage points. The x-axis denotes years. The dashed lines display the 68% confidence bands. GEXP=growth rate in government expenditures, xxY=xx-year Treasury yield.

3.5.3 Affine Term Structure Model (NARR-AFF)

The third NARR model specification again confirms the previous results while providing additional view on the actual transmission channels. Stochastic trend τ_t temporarily decreases after a positive spending shock, which pushes yields down across all bond maturities (Figure 3.14), mostly due to a drop in the risk-neutral yields. While the responses of the first and the second cyclical factors $\widetilde{F}_t$ drive certain additional volatility mostly in the risk-neutral yields, the third cyclical factor volatility (the initial and the secondary delayed drop) is the source of volatility in the term premium (see Section 3.3 and Section B.1 for yield factor loadings).

Figure 3.14: Responses in NARR-AFF model to government spending impulse (selected)



Note: The yield response (black) is decomposed to the response of the risk-neutral yield (blue) and the response of the term premium (red) at the bottom panels. The impulses are set as an increase in a growth rate, responses are measured in factor values or yield percentage points. The x-axis denotes years. The dashed lines at the upper panel display the 68% credible intervals. xxY=xx-year Treasury yield.

These observations support the previous discussion on the spending shock transmission, given the shock is identified in a narrative way. The shock causes initial cautious response of economic agents, which transmits through the *real channel* to the lower yields across all maturities. Additionally, NARR-AFF model shows that the initial drop in yields is partially caused by the drop in the term premium. This supports the importance of the *financial market sentiment channel*, as the uncertainty causes demand for Treasures representing safe haven and a certain tool to hedge against the uncertainty.

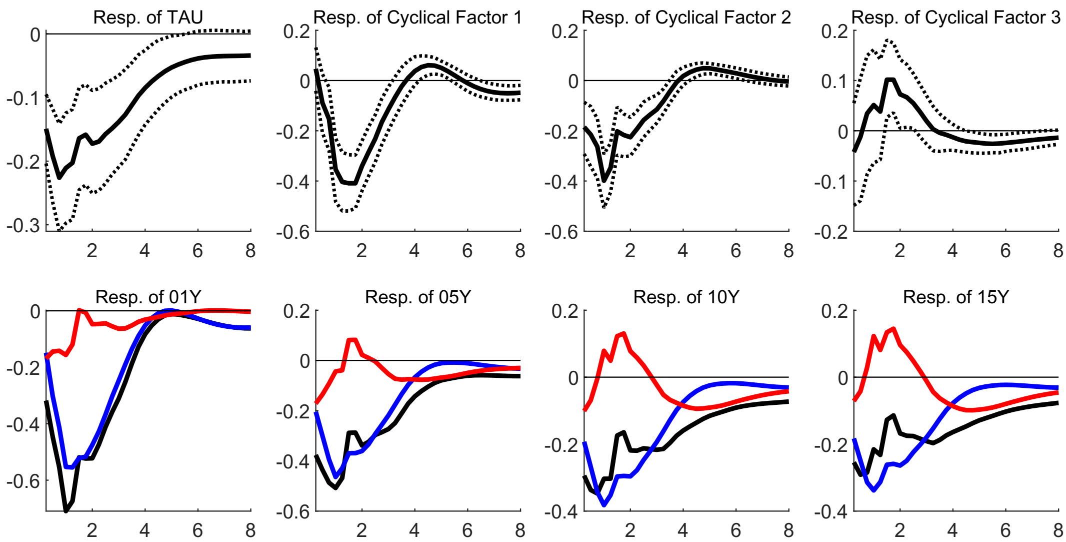
Importantly, the NARR-AFF model specification differs from NARR-YLD and NARR-LSC in the way that the shorter yields switch to a growth instead of the initial drop after several quarters, in case of a positive spending shock. This dynamics is mostly governed by the factors driving the risk-neutral yields, whose switch to positive is statistically significant (Figure 3.14). In the longer yields, the delayed positive response is muted by opposite behaviour of the term premium. Such delayed behavior is very close to the results displayed at SVAR-AFF model. The risk-neutral yields and also the short yields increase thanks to the positive effects of the government spending on the real economy (the *real channel*) and possibly also due to a need to finance the additional spending (the *Treasury supply channel*). The longer-term yields are, in turn, affected by simultaneously growing uncertainty and the need for a certain hedging via the safe haven assets (*financial market sentiment channel*), which pushes the yields down and thus compensates the increase in the risk-neutral yield. Unlike the SVAR-AFF model, the evidence on the presence of the *debt sustainability channel* is not strong in NARR-AFF model results.

Finally, the NARR-AFF model version with the FPU index replacing the narrative spending shock again further supports the importance of uncertainty when explaining the yield response to the shock. In the case a mere uncertainty increases, the risk-neutral yields drop and return more slowly, compared with the previous case (compare Figure 3.15 and Figure 3.14). The absence of the positive effect of the delayed realized spending after the FPU shocks implies that the cautious response of economic agents through the *real channel* is more persistent. On the contrary, the pure FPU shock, which may have various possible causes beyond news about future government spending, causes a rise in term premium. In this case, the importance of the *debt sustainability channel* is apparent, while the effect of the flight to quality behavior (the *financial market sentiment channel*) is diminished.

3.6 DSGE-Based Fiscal Policy Shocks

The previous model specification relied on the structural shock identification within VAR framework, either in the sense of Blanchard & Perotti (2002) or using the NARR approach that utilizes figures on future expected spending. However, while VARs have been shown to be successful in capturing the dynamic properties of macroeconomic time-series data, interpreting the statistical relationships in the form of an outcome of VARs estimation back to coherent economic stories may face the fact that the VAR analysis depends crucially on underlying assumptions (linearity and fundamentalness of the shocks) and the identification restrictions. The uncertainties related to the identification are reflected also in our approach

Figure 3.15: Responses in NARR-AFF model with FPU to government spending impulse (selected)



Note: The yield response (black) is decomposed to the response of the risk-neutral yield (blue) and the response of the term premium (red) at the bottom panels. The impulses are set as an increase in a growth rate, responses are measured in factor values or yield percentage points. The x-axis denotes years. The dashed lines at the upper panel display the 68% credible intervals. xxY=xx-year Treasury yield.

in the differences between the results when using the Blanchard & Perotti (2002)-like identification (Section 3.4), that broadly follows the consensus in many specific questions over the government spending shock identification strategy, and the results when using forward-looking approach to shock identification (Section 3.5)—the literature also confirms that fiscal policy shock identification remains a highly controversial issue (see Ramey 2011 and Ramey 2016 for survey on the issue).

A type of model that is not susceptible to this problem is the DSGE model. In this case, economic theory is used to define all the linkages between variables. The tight economic structure allows the modeler to deal with the identification issue but on the cost of loosing much of the flexibility provided by the VARs. The DSGE model builds on the data theory which aims to explain the data exactly and since the theoretical model is never full representation of the complex reality, problems like *i*) under-identification, *ii*) weak- or partial-identification, *iii*) observational equivalence, arises (see Canova & Ferroni 2011). Nevertheless, despite these shortcomings, we believe that the identification of government spending shocks withing the theoretical macroeconomic model which has been shown to match the underlying macro and finance data sufficiently well can provide further insights and add robustness to our analysis. We use therefore the structural dynamic general equilibrium macroeconomic model as yet another approach to identify government spending shocks.

More specifically, we build on the New Keynesian model of Andreasen *et al.* (2018) which has been shown to match particularly well the mix of macro and asset pricing stylized facts related to the yield curve. Prices are rigid in the model economy because firms face Calvo contracts.[22] Households are specific by the preference of early resolution of uncertainty introduced by Epstein and Zin preferences and in addition they the period utility function features consumption habits. To model the interactions between financial markets, monetary policy, and the real economy which has been shown to be important driver of yields in last two decades the model relies on two key features. First, households in the model deposit their savings in a financial intermediary which the financial intermediary invests in short- and long-term bonds and creates a wedge between the policy rate set by the monetary authority and the interest rate on deposits. Second, the Taylor rule of the monetary authority contains the excess return on a longer-term bond and because of the direct mapping between the excess return and term premia the model endogenizes the term structure of interest rates. In other words, as the central bank response to changes in nominal term premia by adjusting the policy rate, the yield curve has impact on the real economy through the policy rate.

The model uses the approach of Rudebusch & Swanson (2012) to include the fiscal policy. The government consumption is affected by the economic growth and financed through lump-sum taxes. Importantly from the perspective of our analysis, the model assumes that Ricardian equivalence holds, i.e., the effect of financing of government spending through deficits does not affect the overall economy.

The model is solved non-linearly up to 3rd order of approximation to ensure time varying risk premia and consequently estimated by generalized method of moments. In the following step, we utilize the estimated model and use Kalman filter to extract time series of government spending shocks, total factor productivity and preferences. The time series of shocks when fed back in the

[22]The full specification of the model in the paper would extend the paper significantly, whereas the aim of the paper is to focus on the shock-yield nexus rather than on the DSGE model itself. Therefore, the reference to Andreasen *et al.* (2018) is used instead to refer on the details of the model that was replicated for the purposes of this paper without any further adjustments.

model exactly replicates the observed time series of GDP, inflation and 3-month nominal interest rate.

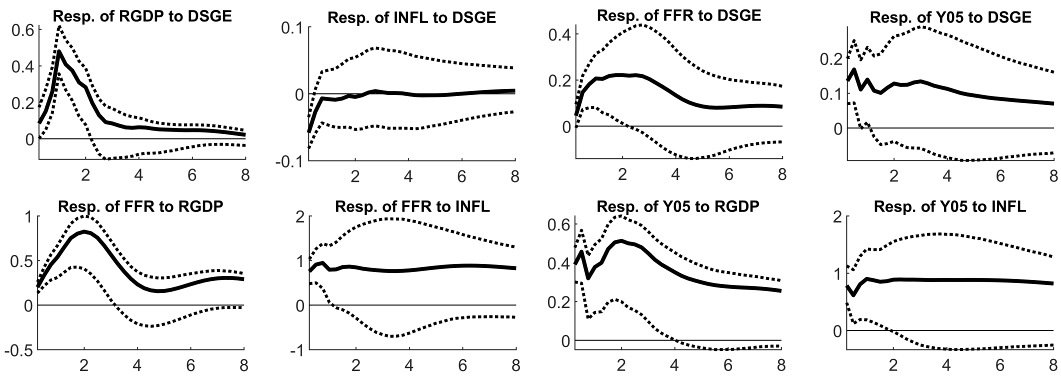
The resulting estimates of government spending structural shocks obtained from the DSGE model are displayed in Figure 3.5, the bottom-right panel. Again, similarly to the other spending series, the peak in 2008–2009 is present; however, the shocks since then are positive under this specification, unlike to the other cases. We utilize the DSGE-based estimates of shocks in our previous framework, i.e., link them with the yield curve within -YLD, -LSC and -AFF models. To do so, we leave the domain of DSGE model and enter the estimated time series for spending shocks into a VAR model similar to the previous models. It may seem surprising to return to VAR modeling after claiming the advantages of using a DSGE model—it would be possible to obtain impulse responses directly from the DSGE model. However, we have multiple reasons to consider such approach as the preferred one: (i) this allows us to present results comparable to other parts of the paper, making the DSGE-based identification a certain robustness check, and focusing on the discussion of effects of various shock specification rather than of various models; (ii) we may again use all three specification of the yield curve, which would otherwise require estimating three different DSGE models; (iii) displaying the impulse-responses within a DSGE model would require including the whole description of the DSGE model and a wider discussion of the model-implied results into the paper, which would leave only a limited space for the other model specifications; (iv) the VAR model variables are the same as used within the DSGE model and the fiscal shocks are ordered as the first, using a Choleski identification, which helps to ensure that the assumptions imposed by the VAR model do not alter the relation between the fiscal shocks and the other variables significantly, compared to the DSGE model.

3.6.1 Single-Yield Model (DSGE-YLD)

The DSGE-YLD specification of the VAR model is close to both SVAR-YLD and NARR-YLD. Compared to the latter, it only replaces the expected five-year spending by the DSGE-based spending shock and orders it as a first in the VAR variable vector. At the same, as compared to SVAR specifications, the DSGE-YLD model uses information on contemporary rather than expected spending, i.e., the DSGE model does not impose strong forward-looking features in the way that would facilitate shock identification several quarters before actually realized, unlike NARR specifications.

Therefore, the results of the DSGE-YLD model are relatively close to the SVAR-YLD results (compare Figure 3.16 and Figure 3.6). The response of both the Fed funds rate and the longer-term yield to a positive spending shock is positive, whereas the short rate responds in a greater extent than the longer-term yield. The responses are statistically significant, although of a lesser magnitude that in the case of the SVAR-YLD model. The interpretation of such responses and emphasis on the *real channel* follows the discussion at the SVAR-YLD model. This finding confirms the robustness of the positive response of the yields on an expansionary spending shock in case the shock is identified close to the actual spending realization.

Figure 3.16: Impulse-responses in DSGE-YLD model (selected)

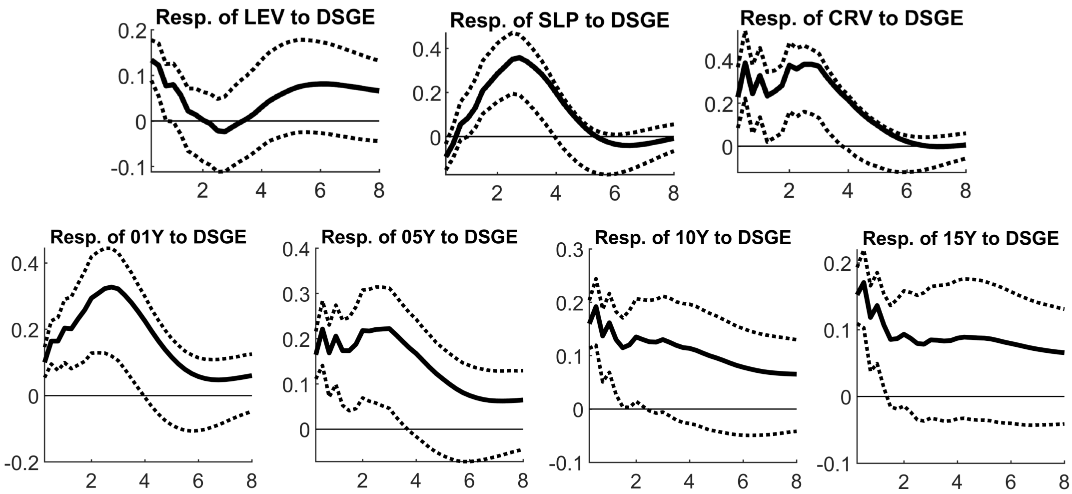


Note: The impulses are set as an increase in a growth rate or a yield by one percentage point, responses are also measured in percentage points. The x-axis denotes years. The dashed lines display the 68% confidence bands. RGDP=real GDP growth rate, DSGE=the DSGE-based spending shock, INFL=annual rate of inflation, FFR=Fed funds rate, Y05=five-year Treasury yield.

3.6.2 Level, Slope and Curvature Model (DSGE-LSC)

The DSGE-LSC model specification is, analogously to the previous cases, close to the DSGE-YLD specification, with the Fed funds rate and five-year yield being replaced by the level, the slope and the curvature of the yield curve. This model broadly supports the findings of DSGE-YLD specification as well as the SVAR approach to shock identification—the level increases immediately after the shock, whereas the slope only with a certain delay. This translates to responses in both short yields (initial increase further increased after several quarters) and long yields (initial increase gradually diminishing). Compared to the findings of SVAR-LSC specification, the secondary increase in longer-term yields is missing in this case. That means that whereas the positive propagation of the expansive fiscal policy shocks through the *real channel* is supported also by DSGE-LSC model specification, the importance of the *debt sustainability channel* is not supported by these results.

Figure 3.17: Impulse-responses in DSGE-LSC model (selected)

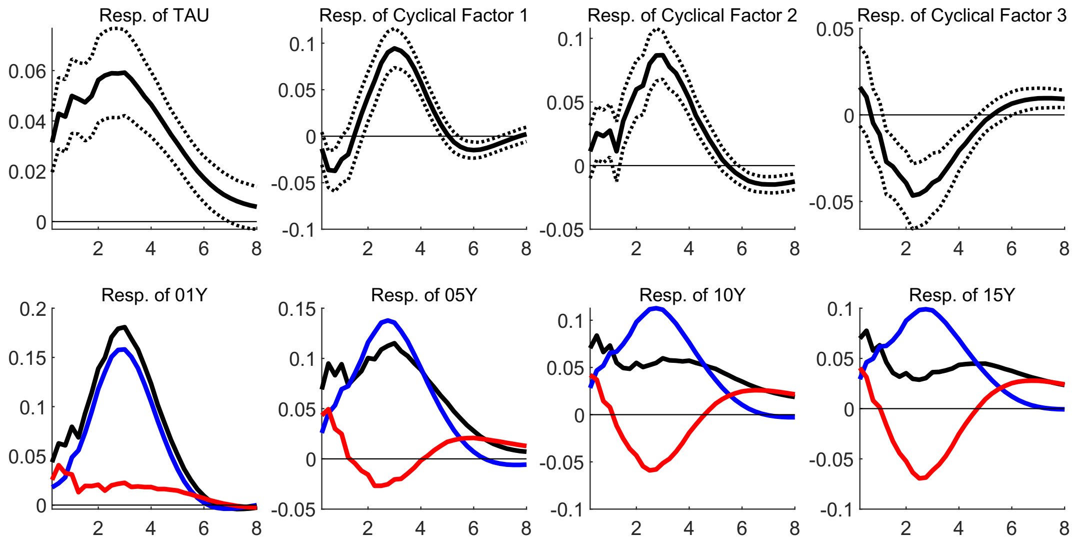


Note: The impulses are set as an increase in a growth rate by one percentage point, responses are measured in factor units. The x-axis denotes years. The dashed lines display the 68% confidence bands. DSGE=the DSGE-based spending shock, LEV=the level, SLP=the slope, CRV=the curvature, xxY=xx-year Treasury yield.

3.6.3 Affine Term Structure Model (DSGE-AFF)

Finally, the DSGE-AFF specification utilizes yield curve factors from the affine term structure model. The responses of the stochastic trend τ and the three cyclical factors are similar to the results of SVAR-AFF, only with the difference in the τ response that converges more quickly in the DSGE-based shock case (Figure 3.18). The consequence of such outcome is the growth in the importance of the term premium for explaining the longer-yield movements. Again, the discussion of the results as provided at SVAR-AFF model applies also here: the *real channel* of the response, signaled by the dynamics of the risk-neutral yields, is dominant for the short yields; with increasing maturity, the increase in yields is lower but more persistent due to a presence of the other channels that affect the term premium.

Figure 3.18: Responses in DSGE-AFF model to government spending impulse (selected)



Note: The yield response (black) is decomposed to the response of the risk-neutral yield (blue) and the response of the term premium (red) at the bottom panels. The impulses are set as an increase in a growth rate, responses are measured in factor values or yield percentage points. The x-axis denotes years. The dashed lines at the upper panel display the 68% credible intervals. xxY=xx-year Treasury yield.

3.7 Summary and Discussion of the Results

To summarize the results, the nine model specifications presented provide a complex view on the yield-fiscal policy nexus, the transmission channels, role of risk-neutral expectations and risk premia and the importance of timing of the shocks.

We match the results from the literature focused on the effects of the current spending on the yields. We show that the yields increase after the spending shock actually appears in the government figures and eventually also affect the budget balance, which matches the findings of Dai & Philippon (2005), Ardagna *et al.* (2007) and Laubach (2009). We argue, based on the results of the "SVAR" model specifications and further verified by the "DSGE" specification, that a transmission through the *real channel* is crucial: an expansionary spending shock supports the economic activity, in line with the results of Blanchard & Perotti (2002), which in turn supports expectations about future inflation and monetary policy and eventually driving the yields upwards. Further evidence (decomposition in SVAR-AFF in particular) supports the idea that *Treasury supply channel* is partially responsible for the increase in yields after the shock, although this effect is lesser than of the *real channel* in line with the recent literature discussing whether the "crowding-out" or the "crowding-in" effect of the fiscal spending prevails (Moretti *et al.* 2019). Finally, the volatility in the term premium further affects the yields at the medium-term horizon through the *financial market sentiment channel* and in the long-term through the *debt sustainability channel*, which is close to some claims in Bauer (2017).

We further confirm simultaneously the view of Ramey (2011) that the timing of the shocks matters. The "NARR" specification of models allows us to demonstrate the behavior of the yield curve during period between the moments when fiscal policy shock becomes expected by economic agents and when it is actually realized. As the "NARR" model specifications demonstrate, yields initially drop, which we explain by a cautious response of economic agents related to future economic and policy uncertainty. NARR-AFF further shows that this initial drop is caused by both the *real channel*, when economic agents adjust their economic behavior, and the *financial market sentiment channel* due to short-lived flight to safety which is caused by needs of the agents to "hedge" against the uncertainty. After the initial response lasting several quarters, the above-mentioned increase in yields appears instead, matching the previously made claims about the transmission once the government spending is realized and financed on the market. However, as the NARR-LSC model results hint, the delayed increase in yields may only compensate the initial drop, as their increase after the monetary policy realization above the original level is not statistically significant. But overall, we claim that the different identification of shocks does not contradict the previous claims but rather extend it by additional information about the initial response of yield before the spending is realized and therefore also making the latter increase in yields smaller when compared to the initial situation.

We also use FPU index to further verify the claim that the reaction to uncertainty is a plausible explanation of the drop in yields. The results for NARR-AFF model with the expected spending replaced by the FPU index clearly support the view that the drop in Treasury yields may be attributed to a reaction of markets and economy as a whole to the uncertainty. We therefore find further support for the discussion in Bauer (2017) mentioning that the fiscal and geopolitical uncertainty contributes to lower Treasury yields.[23] More specifically, in our

[23] And more generally, our evidence on the importance of the uncertainty when understanding the transmission of fiscal policy shocks to the yield curve matches the findings of the broader literature that demonstrates the importance of uncertainty on the economy as a whole. For

case, while the "pure" FPU shock without a necessary subsequent fiscal policy expansion makes the drop in yields more severe and more persistent, compared to the case when the fiscal policy expansion follows, the response of longer-term yields is also affected by a growth in risk premia: The Treasuries do not represent a safe haven asset in case of a FPU shock and the *debt sustainability channel* dominates the *financial market sentiment channel* in this case.

3.8 Concluding Remarks

The paper shows the impact of government expenditures on the yield curve in the US. The approach bridges multiple views from the literature. By following the fiscal foresight literature (Ramey 2011 in particular), we show the importance of the cautionary responses of the economic agents that need to "hedge" against future possible adverse developments in line with the theoretical model of Horvath *et al.* 2017, which leads to a temporary drop in yields prior to fiscal policy realization. On the other hand, we find that the fiscal expansion shock identified at the moment when the fiscal policy is realized leads to an increase in yields. These two seemingly contradictory results in fact provide single whole picture on the transmission of the fiscal policy into Treasury yields: the initial uncertainty-induced drop in yields is later exchanged by their increase, following real effects of the spending on the economic activity and the need to finance the spending through newly issued bonds. Such finding is broadly in line with the view of Leeper *et al.* (2012) on the importance of understanding the dynamic properties of the fiscal policy news.

The literature (Gale & Orszag 2003; Dai & Philippon 2005; Ardagna *et al.* 2007; Laubach 2009) frequently emphasizes the debt financing and uncertainty related to the government indebtedness, i.e., the *Treasury supply channel* and the *debt sustainability channel*, as important causes of rising yields after the expansionary fiscal policy is realized. However, the literature on the effect of the government expenditures as a whole, rather than the possible secondary effect of the indebtedness, is rather scarce and inconclusive (Evans & Marshall 2007). We bridge this gap by our research and argue that the *real channel* that reflects the real economic consequences of fiscal expansion and the impact on inflation and monetary policy response is crucial for explaining the response in yields. This

example, Bloom (2009) and Bloom *et al.* (2018) focus on the effect of uncertainty on the business cycle dynamics, whereas Pastor & Veronesi (2012) analyse the linkage between fiscal policy uncertainty and stock prices.

is roughly in line with the textbook economic theory that predicts the positive effect of government spending on the aggregate demand (Baxter & King 1993; Fisher & Turnovsky 1992) together with the questions related to the dominance of the "crowding-out" or "crowding-in" effect (Moretti *et al.* 2019).

The discovered importance of the *real channel* relates to both the initial drop in yields after the fiscal expansion becomes expected and to the latter increase in yields after it is realized. Building on this finding, our results also provide important view on the possible interaction of fiscal and monetary policy. Without providing further evidence, we argue that this can be narratively documented by the observed sensitivity of Treasury yields in relation to expectation to the results of the U.S. Presidential election in 2020, which was in the market commentaries frequently related to different amounts of fiscal stimulus as proposed by Democratic and Republican candidates—the chance of a higher fiscal stimulus was largely related to a chance of sooner exit from the extremely supportive Fed policies. Such view, although preliminary, proposes an interesting future extension of the research into the area of the changes of interactions between fiscal and monetary policy under low-yield environment, quantitative easing policies and also the breakout of the Covid-19 crisis.

We further emphasize that the initial drop in yields is closely linked to uncertainty. When using the shock into news based FPU index by Baker *et al.* (2016) instead of the expected spending shocks, the drop in yields is larger and the term premium instead increases with some delay, compared to the response of the yields when the uncertainty is linked to a future fiscal expansion. By generalizing such observation, we claim that the degree of uncertainty perceived by the financial markets and economic agents in relation to the fiscal policy news is an important attribute of the fiscal policies and has material impact on the financial markets. Put differently, in case a clear communication with only limited uncertainty is be linked to changes in fiscal policy, or the expected future increase in yields due to the fiscal shock is significant, the initial drop in yields might not be present. On the other hand, in case the uncertainty is significant without expected subsequent expansionary fiscal policy, the drop in yields may temporarily decrease the costs of the debt service, with a possible consequence of over-optimistic future debt service projections and, therefore, the risk of further extension of the planned fiscal expansion beyond the sustainable levels. Such risks may later translate in a rise in yields through the *debt sustainability channel* and therefore should be carefully evaluated by policymakers.

Given the specific position of Treasuries as a global safe haven instrument and the limited risk of default of the U.S. government, a possible next step would be to extend the analysis to a panel of countries. This would facilitate generalizing the results and could provide further important contribution of the research for understanding the uncertainty related to the fiscal policy, for example in the case of developing countries that are more sensitive to geopolitical uncertainty shocks and capital flows compared to the U.S.

Chapter 4

The Czech Government Yield Curve Decomposition at the Lower Bound

4.1 Introduction

In his speech in February 2005, former Fed chairman Alan Greenspan expressed a "conundrum" over the falling 10-year Treasury yield despite increasing Fed funds rate (Greenspan 2005). The prevailing view risk premium being roughly constant over time, making of long yields an average of expected short yields, proved insufficient. In order for the Fed to understand and steer the long yields, understanding of the factors affecting the yields—beyond the monetary policy conduct—needed to be developed. Indeed, after a wide discussion among researchers, a drop in the risk premium was identified as the source of the decline of 10-year yields (Backus & Wright 2007). Consequently, the ability of central banks to influence the longer part of the yield curve was admitted to be weaker than originally thought. A proper risk premium modelling and forecasting can help overcome this gap.

A similar need for understanding government bond yield factors emerged also in the case of Czech government bonds. Czech government bond yields have been, like global yields, on a downward trend on average since the global financial crisis started. They have been negative at maturities of up to six years from the beginning of 2016 until mid-2017. This can hardly be explained solely by market expectations of continued low rates or by the lower Czech sovereign risk premium. Therefore, this paper presents an approach to disentangling the Czech government bond yields into multiple components corresponding to the factors crucial for explaining the Czech government bond yield curve dynamics. To add to this, we go beyond the usual separation of the yields to risk-neutral expectation and risk premium: we propose a way to obtain four components which we consider necessary to capture the core dynamics of the Czech government bond yield curve. As we show, this allows us to improve understanding of the yield curve movements, both in terms of historic dynamics and estimating responses of yields to macroeconomic and financial shocks. As with Greenspan's conundrum, we document that some factors may affect yields in a contrary direction than the monetary policy intended, which may weaken the ability of monetary policy to affect the yield of long-term Czech government bonds. As additional contributions, we evaluate the effect of the lower bound on the response of yield curve to shocks. We also comment on the perception of Czech government bonds in times of stress—whether they represent a safe haven or a risky instrument in terms of international capital flows.

In yield curve modeling, the first step is to identify the factors affecting the yield curve and corresponding yield components. The factor-based modeling of yields is frequently based on Nelson-Siegel parametrization of the yield curve using three parameters: the level, the slope and the curvature (Nelson & Siegel 1987). This approach was further developed by Diebold & Li (2006), who developed the DNS model. They see parameters as time-varying factors, which allows representation of yield curve movements by the dynamics of three factors. The usage of three factors seems sufficient, since they explain the dominant share of the yield curve variation (Litterman & Scheinkman 1991) as well as of macroeconomic information (Mönch 2008).

Despite its popularity, the drawback of the relative parsimony of the basic DNS model is that it is not able to separate risk premia from the risk-neutral expectation of future rates.[1] Therefore, in term-structure literature, the Gaussian affine model framework is frequently used instead. This approach builds on the short rate process in the sense of Vasicek (1977). Duffie & Kan (1996) developed a framework for affine modeling which allows solution of wide scale of models relatively easily if certain conditions are satisfied (including the affine relations of factors and other processes). Duffee (2002) further demonstrated how the affine framework may be used to extract the term premia from the model. Further

[1]The DNS framework was later extended by no-arbitrage conditions (Christensen *et al.* 2011) and other elements (Diebold & Rudebusch 2013). That in practice means integration of the DNS and affine framework. We consider the no-arbitrage DNS model as part of the family of Gaussian affine models.

improvement in the specification and estimation of the models was presented by Cochrane & Piazzesi (2009) and Adrian *et al.* (2013); a summary of the most important approaches is outlined in Piazzesi (2010) and Krippner (2015).

One caveat of both the DNS approach and the affine framework is an implicit assumption about the symmetry of yield movements. This means that the probability of yields going up is the same as the probability of yields going down. However, at the lower bound, this assumption is not fulfilled. Shadow-rate affine models were shown to efficiently reflect asymmetry close to the lower bound while offering a tractable framework and relative parsimony (Krippner 2013).

Affine models are able to decompose yields into risk-neutral expectations about yields and term (risk) premia. Term (risk) premia are however still affected by multiple factors, including fiscal and geopolitical uncertainty (Bauer 2017) or inflation uncertainty (Wright 2011). In this paper, we build on an affine approach adjusted by the lower bound; however, we further decompose the risk premia so that we obtain separately (i) "pure" term premium, (ii) credit risk premium and (iii) portfolio effect. Together with the risk-neutral expectations, we obtain four components that correspond to the most important factors affecting the yields of Czech government bonds.

The article is structured as follows. Section 4.2 presents the method used to decompose yield curves. In Section 4.3, the results of the decomposition are shown. In Section 4.4, the analysis focuses on the use of the components to estimate and interpret the response of the Czech government bond yield curve to macroeconomic and financial shocks in a vector autoregression framework. Also, the effect of the lower bound and additional sensitivity testing is presented. The final Section 4.5 concludes.

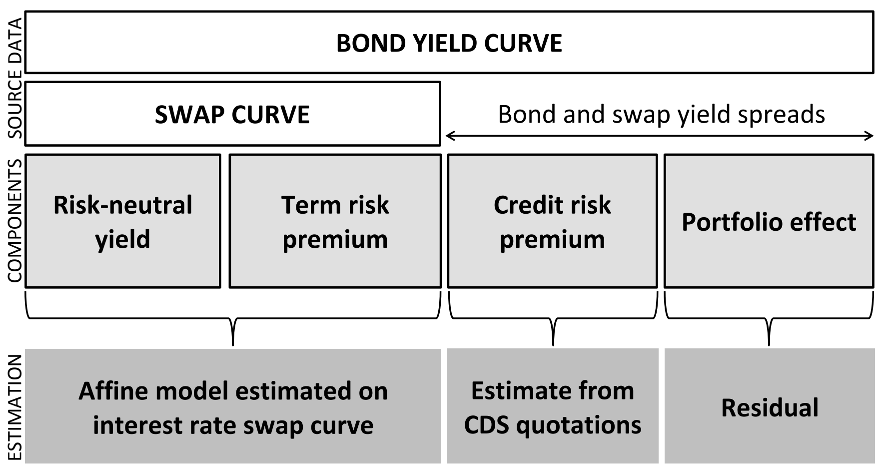
4.2 Yield Curve Decomposition Methodology

4.2.1 Decomposition Rationale and Approach

The yield curve is made up of yields on bonds issued by a single entity with various residual maturities at a specific point in time. The shape of the curve is determined by its level (the yields on the long end of the curve), its slope (the difference between yields on short- and long-maturity bonds) and its curvature (allowing for concave or convex maturity-yield relationship). The relative level of short-term and long-term yields should depend on market expectations about the future path of short-term rates. According to the pure expectations hypothesis, a risk-neutral investor should attain the same yield from investing in a long-term bond as from a series of investments in a short-term bond over a period equal to the residual maturity of the long-term bond. The pure expectations hypothesis offers a simple and attractive interpretation of the yield curve. However, it does not hold in reality, as it does not take risk-averse investors into consideration. In other words, investors perceive long-term investment as uncertain and demand a risk premium.

In the literature (Wright 2011, for example), a frequent approach is to consider the government bonds as default free so that the risk premium is only related to the uncertainty of future evolution of yields (the term premium as described below). However, in the case of Czech government bond yields, the premium for the credit risk was historically also an important source of yield variation. At the same time, Czech government bonds have an exclusive position among Czech financial assets, representing the only safe and liquid (marketable) asset available in Czech koruna and a vehicle within speculative schemes. Consequently, we go beyond the traditional approach and instead of decomposing the yield into two components (a risk-neutral yield and a risk premium), we propose a novel extension of the decomposition. More specifically, we decompose the Czech government bond yield curve into four additive components (see Figure 4.1): a risk-neutral yield, a term premium, a credit risk premium and a portfolio effect. The latter three components together form the full risk premium of Czech government bonds. To keep the model parsimonious, we prefer additive components to a multiplicative approach.

Figure 4.1: Components of the swap and bond yield curves



The risk-neutral yield reflects expectations about future monetary policy and economic developments (ithe expectations hypothesis). If investors expect the monetary policy rate to rise in the future, they also expect the rate of return on holding and regularly reinvesting short-term bonds to go up gradually. The term premium relates to the maturity of the bond and is compensation for interest rate risk.[2] It takes into account investors' uncertainty about the future path of the short-term rate. Committing to long-term bonds will turn out to be relatively less (more) advantageous if future short-term rates are higher (lower) than originally expected. As long-term bonds have higher duration than short-term ones, impact of interest rate changes on long-term bond investors' portfolios is magnified.

Regarding our approach to the decomposition, as an underlying assumption we consider the risk-neutral yield and the term premium to be common for both Czech government bond yields and Czech koruna (CZK) IRS rates. Such an assumption follows the intuition that expectations about the future short interest rates as well as the uncertainty related to them is not dependent on financial instruments. A corollary of this assumption is that the spread between the Czech government bond yield and the CZK IRS is formed exclusively by the other two components: the credit risk premium and the portfolio effect.

To simplify the method, we assume both credit risk premium and the portfolio effect of IRSs equal to zero. This simplification is in line with the nature of the IRS: IRSs contain only a very limited credit risk premium, as no principal is paid, coupon payments are netted and the way IRSs are traded mitigates counterparty risk. An IRS is meanwhile not an investment asset, because it cannot be used to deposit liquidity. The portfolio effect of an IRS is therefore negligible.

The absence of any other components allows the use of the affine class of models (Duffie & Kan 1996; the affine model described in 4.2.2) for the IRS data to be separated into two components. The application of the affine model on the IRS data can be seen as its application on a set of yields of composite bonds, which are risk free in terms of credit risk and are traded on a perfect market (the portfolio effect is not present). In contrast, the portfolio component in the Czech government bond yields can be affected in certain circumstances by specific market effects such as flight to quality, flight to liquidity, search for yield and various types of speculation caused, for example, by unconventional monetary policies and exchange rate regimes. However, these specific effects could

[2] See the discussion in Chapter 1 for the explanation of the term premium from point of view of the macroeconomics and the no-arbitrage pricing.

disrupt the affine model's assumption of market efficiency and the impossibility of arbitrage. The risk-neutral yield and the risk premium estimated using the affine model from government bond yield curves could thus be distorted.

The credit risk premium is a compensation for the risk that bond coupons and principal will not be paid on time and/or in full. This premium tends to increase with increasing maturity. The issuer's position can worsen significantly over time, so, for example, the one-year probability of default in five years' time (the probability of default between the fifth and sixth years) is usually higher than the current one-year probability of default, i.e., the probability of default between now and 12 months from now (Moody's 2017). The credit risk premium is estimated from credit default swap (CDS) quotations for Czech government bonds.[3] The volatility of the CDS quotations was reduced by smoothing them using the three-month moving average. Furthermore, to obtain quotations for each maturity, the Nelson-Siegel function was fitted to these averaged quotations.

To the best of our knowledge, in term structure modeling, such explicit calculation of the credit risk component from CDS quotations has not been used so far. The literature mostly focuses on yields of U.S. government bonds, where the credit risk premium is considered as negligible and rather constant over time, and hence interpreted as a part of the total risk premium. By contrast, in the Czech government bond yield curve, the increase of the credit risk premium significantly affected the yield of longer maturities between 2009-2012 (see Figure 4.2). As a contrasting approach, it would be also possible to estimate the credit risk premium from the Czech government bond yields by using intensity-based modeling of credit risk as in Lando (2009). This approach extends the risk-neutral pricing used in the affine model to include the credit risk premium as well. However, since this approach would further increase the technical requirements for building and estimating the model, we leave this possibility for further research and stick to the estimation of the credit risk premium directly from the CDS quotations.

The portfolio effect of the yield reflects demand for government bonds as an investment asset or a tool usable for speculative trades (Kladıvko 2010). Many investors prefer government bonds to other assets, mainly because of their low

[3]The advantages of this approach are the objective existence of quotations (which should represent the direct cost of hedging credit risk), its forward-lookingness and the availability of a range of maturities in daily periodicity. On the other hand, we also need to take into account certain sovereign CDS market anomalies that may limit the use of CDS quotations as a sovereign solvency indicator (see Komárek *et al.* 2013, Box 4 of CNB 2010 and Box 4 of CNB 2012). Short time series are another potential limitation for some maturities.

credit risk, their relatively high market liquidity, their low haircuts when used as financial collateral and their preferential regulatory treatment. Additionally, government bonds can serve as a tool to perform speculative or arbitrage trades. The portfolio effect could take positive (negative) values if the yield demanded by the investor for holding the bond is higher (lower) than the expected short-term rate plus the term premium and the credit risk premium. The portfolio effect is calculated as a difference between the observed government bond yield and the observed rate of an IRS rate of identical maturity minus the fitted credit risk premium. The average portfolio effect in the model therefore depends on the estimate of the credit risk premium and also includes possible measurement fitting error from the calculation of the credit risk premium. Therefore, in the interpretation of the results, we reflect the fact that certain dependencies between the portfolio effect and credit risk premium may still persist. The portfolio effect may also reflect the supply side of the government bond market: a prospective scarcity of the supply of bonds with certain maturities may be reflected by a lower required yield for those maturities, i.e., lower portfolio effect.

The presented approach does not consider the components to be orthogonal. In practice, the correlation of the term premium and the credit risk premium can be expected to be significantly positive, since both reflect the risk-attitude of investors. In our approach, the correlation is data-driven, i.e., results from the correlation of the term premium priced in the CZK IRS rates and the CDS quotations. The separate estimation of the components does not allow modeling of these variables jointly and utilizing the correlation in the framework. An intensity-based modeling of credit risk Lando (2009) could bridge their relations in a joint framework, which however goes beyond the extent of this paper and is left for future research.

4.2.2 Interest Rate Swap Curve Decomposition

To decompose the IRS curve, we use an affine model (Duffie & Kan 1996, or Málek 2005). The basic building block of this model is its assumption that there are several underlying factors (X_t) that determine the entire term structure of rates. The affine model presented here uses three factors, in line with the standard approach employed in the literature (Litterman & Scheinkman 1991). These factors are unobservable, and we estimate them within the model. In the model, their dynamics under a risk-neutral $\mathcal{Q}$-measure are set in the form of a mean-reverting (Ornstein-Uhlenbeck) process (Krippner 2015):

$$dX_t = \kappa(\theta - X_t)\,dt + \sigma dW_t \ , \tag{4.1}$$

where W_t is a 3-dimensional independent Wiener process, θ is a 3×1 vector representing the level of the mean reversion, κ is a 3×3 matrix determining the speed of the mean reversion and σ is a 3×3 matrix allowing the innovations to X_t to be correlated.

Since the model falls into the family of affine models, affine representation is used to obtain both the market price of risk λ_t:

$$\lambda_t = \sigma^{-1}(\gamma + \Gamma X_t) \tag{4.2}$$

and the short (infinitesimal) rate r_t:

$$r_t = \alpha_0 + \alpha_1 X_t \ . \tag{4.3}$$

From the short rate, the longer rates $R_t(\tau)$ of any maturity τ are derived by applying the expectation hypothesis under the $\mathcal{Q}$-measure. The expected path of the factors is obtained from (4.1). The expected short rate path under the $\mathcal{Q}$-measure is then again calculated by the transformation in (4.3). The longer rates $\widehat{R}_t(\tau)$ are derived by integrating the short rate over the expected path:

$$\widehat{R}_t(\tau) = \frac{1}{\tau}\int_0^\tau \left[E_t^{\mathcal{Q}}[r_{t+u}|X_t] - VE(u)\right] du \ , \tag{4.4}$$

where $VE(u)$ is a volatility effect, which corrects the expectations with respect to Jensen's inequality (Heath *et al.* 1992). The Jensen's inequality results from the nature of the expectations hypothesis in terms of bond prices and the convexity of the exponential function:

$$e^{-R_t(\tau)\tau} = E_t^{\mathcal{Q}}\left[e^{-\int_0^\tau r_{t+u}du}|X_t\right] \leq e^{-E_t^{\mathcal{Q}}\left[\int_0^\tau r_{t+u}du|X_t\right]} \ . \tag{4.5}$$

$VE(u)$ value requires calculation of a double integral (Heath *et al.* 1992) and depends only on the maturity and the parameters from (4.3). $\widehat{R}_t(\tau)$ differs from $R_t(\tau)$ by the measurement error, which appears since the time-invariant parameters in the equations (4.1)–(4.3) do not allow us fitting the observed yields exactly.

Under the $\mathcal{Q}$-measure, the investors are risk-neutral, i.e., the term premium does not exist (it is incorporated into the risk-neutral path of the factors). Therefore, to obtain the term premium, the factor process in (4.1) is transformed into a data-generating $\mathcal{P}$-measure. This transformation is performed using the market price of risk λ_t: $d\widetilde{W}_t = dW_t - \lambda_t dt$, where the Wiener process $d\widetilde{W}_t$ is under the $\mathcal{P}$-measure. Given the affine representation in (4.2), the formulas under the $\mathcal{P}$-measure are identical; only the parameters of (4.1) are adjusted (see Duffee 2002, for details). Through the equations (4.3)–(4.5) under the $\mathcal{P}$-measure, the $\widehat{R}_t(\tau)$ is obtained—in this case, it represents only the risk-neutral yield, i.e., these do not fit the observed yields. The term premium is finally obtained as the difference between $R_t(\tau)$ and $\widehat{R}_t(\tau)$ fitted under the $\mathcal{P}$-measure.

A plausible consequence of the affine form of (4.2) and (4.3) is that the affine model under the $\mathcal{Q}$-measure can be solved analytically. This means that the equations (4.1)–(4.5) result in a representation of the fitted yields as a function of the factors and the maturity: $\widehat{R}_t(\tau) F(X_t, \tau)$. The difference between $\widehat{R}_t(\tau)$ and $R_t(\tau)$ under the $\mathcal{Q}$-measure is given only by the measurement error. Moreover, the factors X_t are unobserved, therefore it is necessary to estimate them. As a solution the affine model is specified in a state space representation. The measurement equation linking the observed yields and the factors is given by a no-arbitrage $\mathcal{Q}$-measure pricing equation $R_t(\tau) = \widehat{R}_t(\tau) + e_t(\tau) = F(X_t, \tau)$, whereas the $\mathcal{Q}$-measure factor process represents the state equation. It can be shown (Meucci 2010) that the solution to the continuous time process in (4.1) forms a first-order vector autoregression process for a discrete time step Δt. The final state-space representation is thus:

$$R_t(\tau) = F(X_t, \tau) + e_t(\tau) \ , \tag{4.6}$$

$$X_t = \widetilde{\lambda} + e^{-\widetilde{\kappa}\Delta t}\left(X_{t-1} - \widetilde{\theta}\right) + \nu_t \ , \tag{4.7}$$

where ν_t is a 3×1 vector of random innovations to state variables. (4.7) represents the discrete time process for the factors under the $\mathcal{P}$-measure. Given the state-space representation, the affine model can be estimated using the maximum likelihood, with a Kalman filter (Durbin & Koopman 2012) utilized to obtain the factors.

If interest rates are already close to their lower bound, the probability of them falling further is lower than the probability of them rising. This leads to a violation of the assumptions underlying the affine model —the process W_t in (4.1) is no longer a Wiener process. To take this asymmetry into account, the model uses the concept of shadow rates (Krippner 2013). In this concept, which builds on the model of Black (1995), the yield on investing in a bond equals the sum of the yield on investing in a shadow bond whose yield is not bounded below by zero and the yield from the sale of a bond option. The option bears the right to purchase the bond at such price so that its yield is equivalent to the lower bound value. For details, see Krippner (2013).

In practice, in the shadow-rate affine model, (4.3) holds for the shadow short rate rs_t. The expected value of the observed short rate r_{t+u} entering into (4.4) is then obtained as a sum of the expected shadow short rate and the option effect:

$$E_t^{\mathcal{Q}}\left[r_{t+u}|X_t\right] = E_t^{\mathcal{Q}}\left[rs_{t+u}|X_t\right] + E_t^{\mathcal{Q}}\left[\max\left(r_L - rs_t, 0\right)|X_t\right] \ , \tag{4.8}$$

where r_L is the value of the lower bound. Krippner (2013) derives a closed-form solution for $E_t^{\mathcal{Q}}\left[r_{t+u}|X_t\right]$ in terms of parameters from the equations (4.1)–(4.3). After plugging into (4.4), the whole term structure is derived, i.e., the function $F\left(X_t, \tau\right)$ is obtained. The final formulas are complex and therefore omitted here for parsimony; a complete description can be found for example in Krippner (2015). Due to the option effect, the function $F\left(X_t, \tau\right)$ is not linear in case of the shadow-rate affine model. Therefore, an extended iterative Kalman filter (Durbin & Koopman 2012) is employed in the estimation. However, the shadow rates can still be expressed as an affine transformation of the factors. For this reason, the model still falls into the category of affine models.

To estimate the shadow-rate affine model in its state space representation defined by (4.6) and (4.7), it is necessary to set identifying restrictions. We used the shadow rate stationary Gaussian affine (SR-SGA) model (Krippner 2015, section 4.4.4).[4] The restrictions imposed by the SR-SGA model on the parameters from (4.3) and (4.7) are as follows:

$$\widetilde{\kappa} = \begin{bmatrix} \widetilde{\kappa}_1 & 0 & 0 \\ 0 & \widetilde{\kappa}_2 & 0 \\ 0 & 0 & \widetilde{\kappa}_3 \end{bmatrix} \ , \quad \widetilde{\lambda} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \ , \quad \alpha_1 = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \ . \tag{4.9}$$

[4]We also evaluated the results using an arbitrage-free DNS model specification established by Christensen *et al.* (2011) and extended with the shadow rates by Christensen & Rudebusch (2015). However, due to a relatively low maximum maturity included in the sample, the shadow-rate arbitrage-free DNS model does not converge well and is very sensitive to initial conditions. As described in the next section, we used maturities up to 15 years. Contrary, in case of the US or EA yield curves, maturities 20–30 years are usually available. Apart from the sample, the shape of the Czech yield curve is also slightly different than in case of other countries—the Czech yield curve was never inverted in the sample period.

Furthermore, σ is lower-triangular. The measurement errors $e_t(\tau)$ from (4.6) form a random normally distributed vector with a zero mean and a time-invariant diagonal covariance matrix. The state innovations ν_t from (4.7) are normally distributed with zero mean and a variance given by the σ matrix (derivation can be found in Krippner 2015). The two error vectors are assumed to have a zero covariance matrix.

After the SR-SGA model is estimated, it can be used to decompose the observed rates into the two components. This decomposition is done independently for each period t in the sample. The vector of factors X_t, which was extracted during the SR-SGA model estimation, is the starting point. Using (4.3) and (4.7), the expected path of the factors $\left\{E^{\mathcal{P}}\left[X_{t+j\Delta t}|X_t\right]\right\}_{j=1,2,\ldots,T/\Delta t}$ and the short rate $\left\{E^{\mathcal{P}}\left[r_{t+j\Delta t}|X_t\right]\right\}_{j=1,2,\ldots,T/\Delta t}$ is calculated, where T represents the longest maturity in the sample (in years). For any maturity $\tau < T$, the average expected short rate $\Delta t/\tau \sum_{k=1}^{\tau/\Delta t} E^{\mathcal{P}}\left[r_{t+j\Delta t}|X_t\right]$ represents the risk-neutral component of the yield $\widehat{R}_t(\tau)$. As with (4.4), the volatility effect adjustment applies. The expectations are under the $\mathcal{P}$-measure: the risk-neutrality of the component means that it is calculated as an average of future short rates (without any risk premia). The second estimated component—the risk premium (which is equal to the term premium in case of the swap rates)—is then obtained as the difference between the fitted swap rate $\widehat{R}_t(\tau)$ and the risk-neutral component.

4.3 Decomposition of the Czech Government Bond Yield Curve

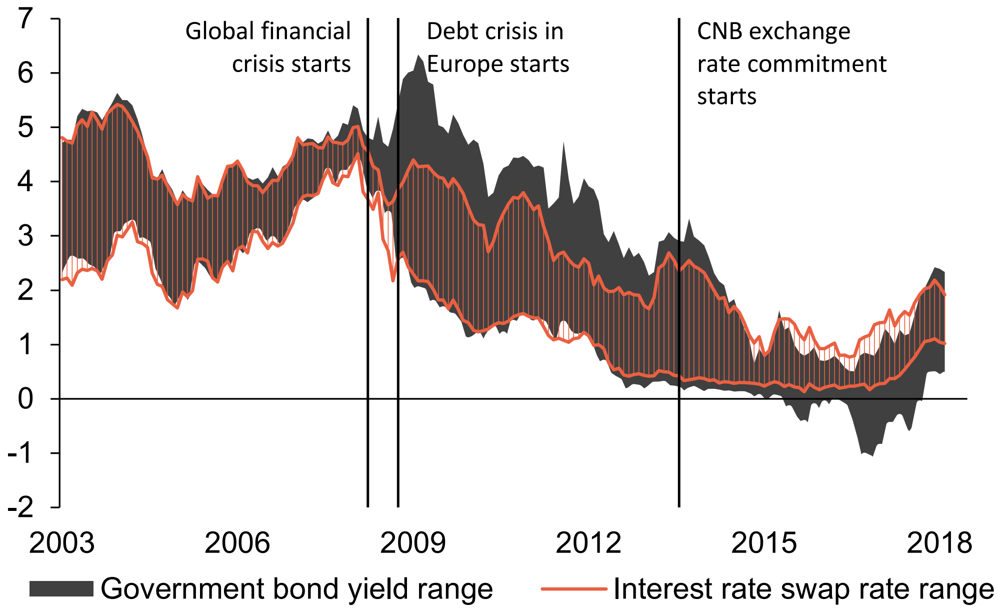
The yield curve is decomposed using the yields on zero-coupon bonds of relevant maturities, since those yields are not affected by the size and distribution of the coupons over the life of the bond and hence are an exact indicator of the rate of return demanded for investing for the relevant time period.[5] For this reason, a zero-coupon curve was constructed using Czech government bonds in Czech koruna. As the risk-neutral yield and the term premium are estimated using IRS rates, it was also necessary to construct a zero-coupon koruna IRS curve. The two zero-coupon curves were constructed for maturities of 1 to 15 years[6] as

[5]The use of yield to maturity of coupon bonds could potentially lead to underestimation of the yields demanded for a given maturity (Livingston & Jain 1982).

[6]The range of maturities considered was chosen with regard to data availability and quality. Bonds with maturities of less than one year are not used in such studies because their prices can be distorted by specific effects due to lower liquidity (BIS 2005). In addition, Czech koruna

of the end of each month over the period of 7/2003–03/2018. The Fama-Bliss bootstrap method (Fama & Bliss 1987), which assumes constant forward rates among the closest maturities, was used for the construction. The advantage of this method over the alternatives (such as Nelson & Siegel 1987, or Svensson 1995)[7] consists in its ability to replicate any yield curve shape exactly, which eliminates problems with imperfect fit on some segments of the curve.

Figure 4.2: Ranges for zero-coupon Czech government bond yields and CZK IRS rates (in %)



Source: Bloomberg, Prague Stock Exchange, MTS Czech Republic, Thomson Reuters, authors' calculations.

Note that the ranges are between one-year and fifteen-year maturities. The vertical lines mark the last monthly observation before the event described. The start of the global financial crisis is related to the collapse of Lehman Brothers in September 2008. The start of the debt crisis is related to the negative assessment of Greek public finances by the International Monetary Fund and the European Commission in February 2009.

IRS are not available for maturities of less than one year. The time series for bonds and IRS with maturities of over 15 years are shorter and their prices may be less reliable due to their lower trading volumes. The empirical strategy assumes the quotes stated for both bonds and IRS are reasonable. Surveys conducted by CNB and market intelligence suggest good liquidity of Czech koruna IRS up to 10 years. There is also certain turnover above 10 years which allows market participants to deal with market makers at their stated quotes. The liquidity of IRS is comparable with that of Czech government bonds, which are also less liquid at longer maturities. The usability of IRS for yield curve construction is further confirmed by EIOPA's current use of IRS (up to 15 years) rather than bonds for discounting insurers' liabilities for regulatory purposes.

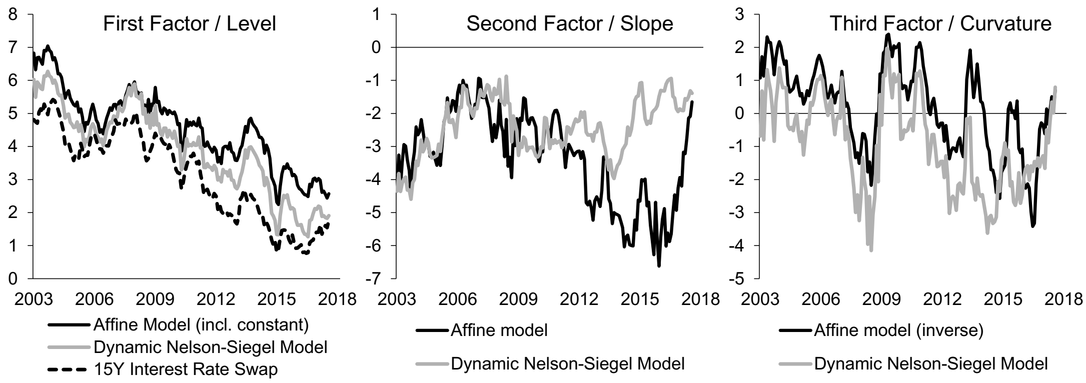
[7]Previous works on yield curve construction from Czech government bonds that use Nelson and Siegel, and Svensson models include Hladíková & Radová (2012), Kladıvko (2010) and Slavík (2001).

The maturity spreads for zero-coupon GB yields and IRS rates in 2003–2018 show mixed developments (see Figure 4.2). Until the outbreak of the global financial crisis in September 2008, yields and rates followed similar patterns. This is consistent with the findings in Kladıvko (2010). From then until the second half of 2009, yields were affected by the fear of the emerging debt crisis in Europe. Owing to the responses of the various relevant authorities to the crisis, yields began to trend downwards in mid-2009 and a positive gap opened up between yields and rates at longer maturities. At the end of 2013, yields started falling faster than rates—until 2015 for long maturities and then exclusively for short maturities. It is clear from this simple historical excursion that yields and rates were affected by different factors with different intensity, including for individual maturities.

The factors X_t resulting from the affine model are shown in Figure 4.3. To understand their dynamics, we also estimate DNS model (Diebold & Li 2006). DNS results in three yield factors with straightforward interpretation, following the Nelson & Siegel (1987) function: the level of the yield curve, its slope and its curvature. As is obvious from Figure 4.3, the factors obtained from the affine model are not far from the DNS factors, which therefore can be similarly interpreted level, slope and curvature. Such a finding is important for understanding the extent to which the non-linearity embedded in both affine and DNS framework could affect the results of the autoregression analysis presented in Section 4.4. Both the long end of the yield curve (the level) and its short end (instantaneous rate as a combination of the level and the slope) preserve linearity; non-linearity is related only to the yields between. Therefore, although non-linearity might be an issue in the autoregression analysis below, the results will be to a certain extent always anchored by the linearly dependent ends of the yield curve. A certain non-linearity issue is also related to the option effect in the shadow-rate model. We show in Section 4.4 to what extent the option effect, i.e., the binding lower bound, affects the results.

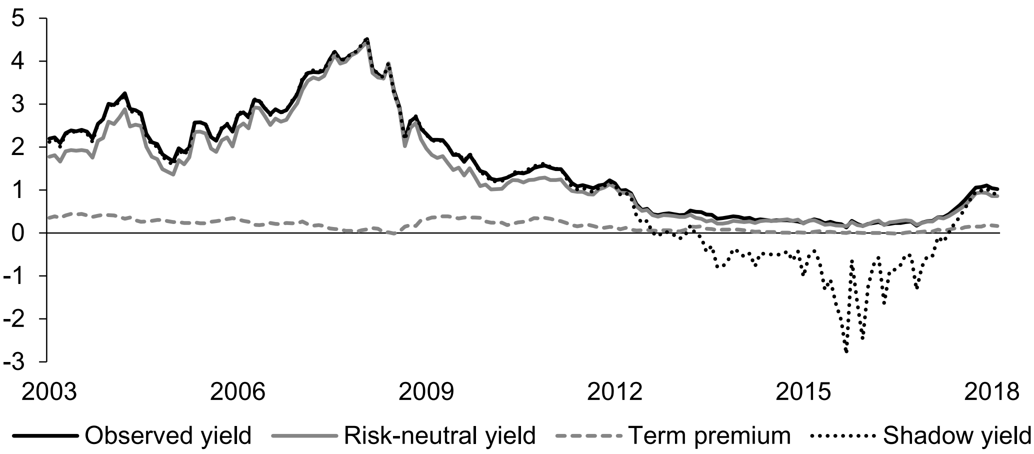
The crucial ability of the affine model is to decompose the IRS rate into the risk-neutral yield and the term premium (see Figure 4.4 and Figure 4.5). The results show that the model generates components in line with general intuition. The term premium of the short rate is rather insignificant, whereas for the longer maturity, it explains a significant share of the rate movements. The term premium for the longer rates behaved countercyclically in the period 2005–2007, which led to a smaller increase of the long rates, compared to the

Figure 4.3: Affine model factors (values of factors, multiplied by 100)



short end of the term structure. Such behavior was widely discussed in terms of U.S. yields (Greenspan 2005). From these observations, we conclude that the model-generated components have plausible properties.

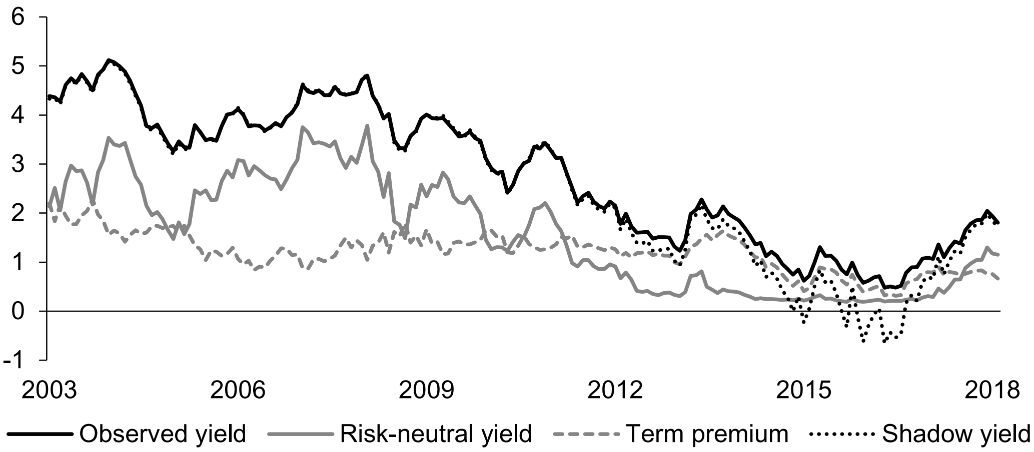
Figure 4.4: One-year IRS rate decomposition (in %)



Source: Bloomberg, Prague Stock Exchange, MTS Czech Republic, Thomson Reuters, authors' calculations

Figure 4.4 and Figure 4.5 also display the estimated shadow 1-year and 10-year IRS rates. Although estimation of the shadow rates themselves was not the main aim of the paper, their evolution offers interesting insight into the monetary policy stance over the lower bound period. More specifically, until 2012, the shadow rates were almost identical to the observed rates. However, after approaching the lower bound in 2012, the shadow short rate gradually decreased to -1%, where they remained for some time. However, during 2015-16, with the growth of the CNB balance due to the forced intervention to keep the exchange rate floor, the shadow short rate further decreased up to -3%. Longer

Figure 4.5: Ten-year IRS rate decomposition (in %)



Source: Bloomberg, Prague Stock Exchange, MTS Czech Republic, Thomson Reuters, authors' calculations

shadow rates followed a similar evolution, although the drop of the shadow rates was much smaller, since the longer observed rates are more distant from the lower bound. During 2017, as the exchange rate floor was exited and the monetary policy rates were increased, the shadow rates returned to positive values, again very close to the observed values.

The estimated values of the affine model parameters and the statistical properties are presented in Appendix C. The overall fit of the model is good (see Figure C.1 and Figure C.2). Measurement error contains residual autocorrelation and heteroscedasticity (see Appendix C), which is a consequence of the changing ability of the model to fit various shapes of the yield curve. However, the measurement error is low, its absolute value on average does not exceed 2 b.p. Therefore, the consequences of the residual patterns are expected to be negligible.[8]

To obtain the credit risk premium, month-end CDS quotations for maturities of 1–5, 10, 20 and 30 years were used in the estimation. We included CDS quotations with 20-year and 30-year maturities (which were not included in the yield sample) in the estimation because of the absence of quotations for 15-year CDS. After smoothing them by a three-month moving average, the Nelson-Siegel function was used to obtain the credit risk premium values for all required maturities. Due to the limited liquidity on the Czech government bonds CDS

[8]Our approach to the affine model estimation and decomposition is in line with the best practices (see Krippner 2015, for discussion). Therefore, we are not much concerned with the properties of the measurement error. Instead, we consider the plausible properties of the components and reasonable implied shadow yields as a sufficient check of the model quality.

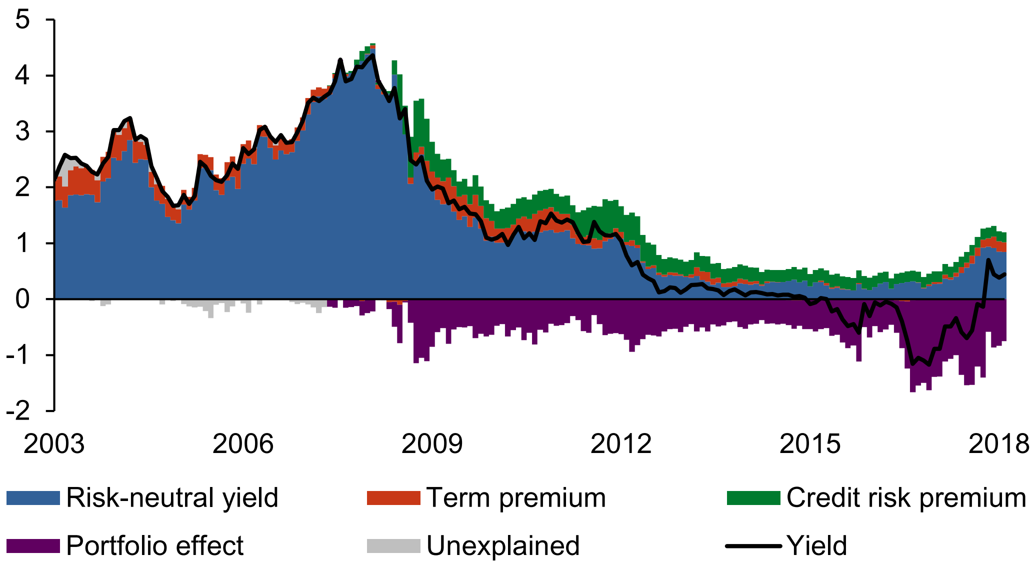
market[9], CDS quotations for Czech public debt of shorter maturities are close to those of longer maturities. However, this was not reflected in the yields on Czech GBs of short maturities. The Nelson-Siegel function was therefore specified so that the credit risk premium converged to zero with decreasing maturity, which is in line with the economic intuition.

The zero-coupon Czech government bond yield curve was decomposed into four introduced components for one-year and ten-year maturities (see Figure 4.6 and Figure 4.7). In the case of the one-year bond, yield was made up predominantly of risk-neutral yield until the global financial crisis broke out in 2008 (see Figure 4.6). From the end of 2008 onwards, the one-year bond yield declined due to falling risk-neutral yield. The decline in this component was linked with market expectations that short-term rates would stay very low. In addition, starting in the second half of 2008, key central banks gradually released large amounts of liquidity as part of their monetary and lender-of-last-resort policies. For reasons of flight to quality and search for yield, Czech government bonds represented an attractive opportunity for foreign investors. Owing to the negligible risk of sovereign default over such a short time scale, the credit risk premium was relatively low in the period under review. The negative portfolio component was linked with investors' preference for holding shorter-maturity bonds at a time of market stress. In 2015, the portfolio component exceeded all the other components combined for the first time and the one-year bond yield thus turned negative. Since then, the yield on short-maturity Czech GBs has reflected strong interest among foreign investors speculating on appreciation of the Czech koruna against the euro upon the exit from the CNB's exchange rate commitment combined with a relatively limited supply of the bonds of certain maturities (see CNB 2017, section 2.1). Since 2017, monetary policy normalization has led to an increase of the yields through both higher risk-neutral yield and in absolute terms decreasing portfolio effect.

The significance of the different components on the level of the ten-year Czech GB yield changed substantially over the 13 years under review (see Figure 4.7). Until the global financial crisis broke out, ten-year bond yields were almost equal

[9]Data from trade repositories available to the CNB indicate the Czech sovereign CDS turnover is rather limited. The most frequent maturity is 5y (about 35% of total turnover by notional principal), followed by maturities of 1-4 years. Maturities longer than 5 years are rare (jointly about 15% of turnover) and maturities longer than 10 years virtually nonexistent. The turnover substantially declined when the market tempered after the debt crisis in Europe subsided. Nevertheless, the low turnover does not necessarily imply illiquidity as long as the market makers are willing and ready to transact at the quotes they contribute.

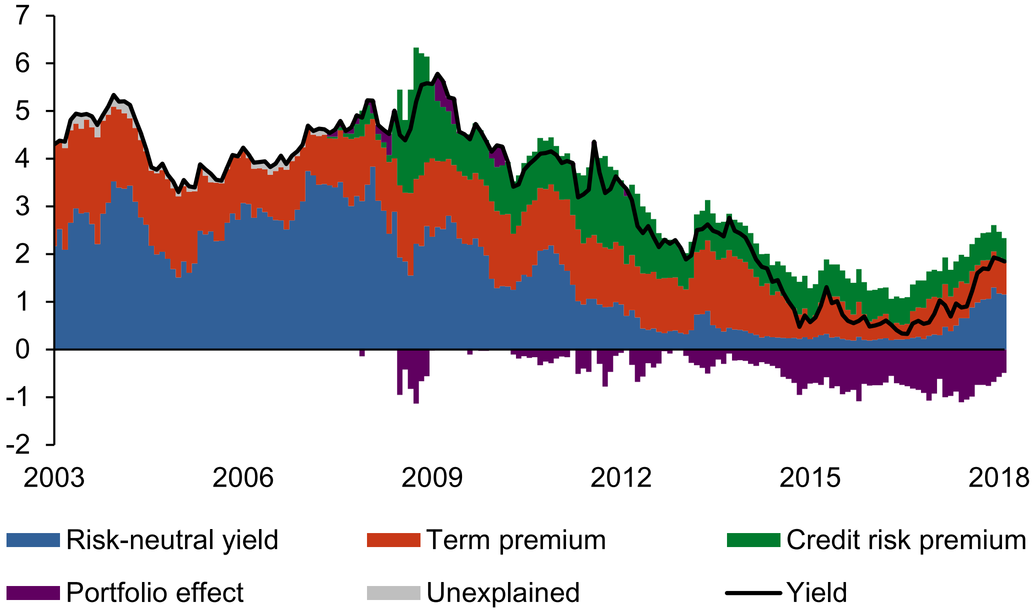
Figure 4.6: Decomposition of the one-year government bond yield (in %)



Source: Bloomberg, Prague Stock Exchange, MTS Czech Republic, Thomson Reuters, authors' calculations
Note that reliable data on CDS quotations are not available until 2008. As a result, the difference between the bond yield and the swap rate could not be decomposed and is reported as unexplained.

to IRS rates of the same maturity. The risk-neutral yield and the term premium each made up around half of the yield. When the US investment bank Lehman Brothers collapsed in mid-September 2008, the global financial market situation worsened sharply. Uncertainty and risk aversion increased, giving rise to higher market price volatility. Owing to the high level of global market integration, the market stress passed to the Czech GB market, as evidenced by growth in the credit risk premium. In mid-October 2008, market liquidity on the Czech GB market dropped sharply as a result of excess supply of Czech GBs from foreign institutional investors. The CNB responded by introducing extraordinary liquidity-providing repo operations in which Czech GBs were accepted as eligible collateral for the first time. This fostered a slight reduction in the credit risk premium. For the same reasons as for the one-year bond, the risk-neutral yield and the term premium began to fall in mid-2008. The term premium increased in late May/early June 2013 in response to a change in market expectations about the timing of the tapering of bond purchases by the Fed in the QE3 program. This change in expectations triggered an unusually sharp price adjustment in a whole range of asset categories across global markets, accompanied by market turbulence. In November 2013, however, the ECB reduced its base rate and in

Figure 4.7: Decomposition of the ten-year government bond yield (in %)



Source: Bloomberg, Prague Stock Exchange, MTS Czech Republic, Thomson Reuters, authors' calculations

Note that zero-coupon yields are displayed and decomposed. Reliable data on CDS quotations are not available until 2008. As a result, the difference between the bond yield and the IRS rate could not be decomposed and is reported as unexplained.

June 2014 it announced the use of other unconventional instruments, including a plan to purchase euro area GBs. In November 2013, the CNB started to use the koruna exchange rate as an additional monetary policy instrument. This combination of measures and a relative scarcity of supply led not only to a fall in the term premium of the ten-year bond, but also to a negative portfolio component. From 2011 onwards, the credit premium and the portfolio component were also affected by the debate about, and subsequent phasing in of, new financial market regulatory measures (Basel III, CRD IV/CRR). A signal of preferential treatment of GBs in the capital and liquidity requirements was sent out to the market.

In order to confirm the theoretical interpretation of the estimated components, their profiles were compared with those of selected macroeconomic and financial variables with which they should theoretically be closely linked. Besides that, we ran correlation analysis between the components and the macroeconomic and financial variables. The correlation analysis was run on monthly changes of components and variables (reported in Table 4.1) and also on their levels (Kučera *et al.* 2017).

Table 4.1: Correlation of monthly changes between the components of the ten-year zero-coupon bond and economic and financial variables

Variable (category and name)	Risk-neutral yield	Term premium	Credit risk premium	Portfolio effect
Macroeconomic				
Inflation (CPI)	0.08	0.05	-0.21 (**)	0.15
GDP growth	-0.04	0.06	-0.20 (**)	0.01
CZK/EUR exchange rate	-0.07	0.05	0.21 (**)	-0.13
Short interest rates and market expectations				
CZEONIA index	0.01	0.10	-0.06	-0.05
CNB 2W repo rate (current)	0.18 (**)	-0.08	-0.28 (***)	0.22 (**)
3M PRIBOR	0.40 (***)	-0.31 (***)	-0.13	0.14
3M OIS in CZK	0.24 (***)	-0.22 (***)	-0.20 (**)	0.20 (**)
CNB 2W repo rate (1Y expectations)	0.37 (***)	-0.17 (**)	-0.56 (***)	0.29 (***)
Inflation (1Y expectations)	0.05	-0.04	-0.14	-0.02
Fluctuations in short interest rates and market uncertainty				
Variability of inflation	-0.20 (**)	0.13 (*)	0.17 (*)	-0.06
Variability of 1Y expectations: inflation	0.06	-0.05	-0.07	0.19 (**)
Variab. of 1Y expec.: CNB 2W repo rate	-0.16 (**)	0.13	0.15	-0.14
VIX volatility index	-0.07	-0.01	0.24 (***)	0.01
Credit risk of Czech state and Czech interbank market				
Czech GBs issued/GDP	-0.23 (**)	-0.08	0.02	0.17
5Y CDS spread for Czech GB	0.06	-0.16 (*)	0.54 (***)	-0.11
Spread: 3M PRIBOR and 3M OIS	0.09	-0.02	0.15	-0.13
Spread: Czech and German 5Y GB yields	0.21 (***)	-0.22 (***)	0.26 (***)	0.28 (***)
Investment flows				
Czech GB trading volume	0.08	-0.04	-0.06	0.13
Proportion of foreign holders of Czech GBs	0.09	0.06	0.05	0.08
Profit on hedged investment in Czech GBs	-0.14 (*)	0.21 (***)	-0.21 (**)	0.15
Net portfolio and other investment in balance of payments	0.02	-0.15 (*)	0.07	-0.06

Source: Bloomberg, CNB, MTS Czech Republic, Prague Stock Exchange, Thomson Reuters, authors' calculations

Note that the asterisks refer to statistical significance at 1% (***), 5% (**) and 10% (*) levels. The explanatory power of the correlations may be limited by the short length for some of the time series. Variability is measured by the standard deviation of the last four monthly observations. The hedged profit expresses relative profit on CNB deposit or two-year Czech government bond as compared to ECB deposit or two-year German government bond, respectively, taking into account the spot and forward exchange rates (similarly to covered interest parity).

The risk-neutral yield should correspond to market expectations about future short-term rates. A comparison with analysts' expectations about the CNB's two-week repo rate one year ahead confirmed this theoretical assumption (Kučera *et al.* 2017). The dynamics of risk-neutral yields turned out to be more closely correlated with the dynamics of expected monetary policy rates than with that of actual policy rates (see Table 4.1). When considering levels correlation, the correlation between the risk-neutral yields and expected policy rates was the highest among all investigated variables (0.96).

The term premium should theoretically be closely correlated with the level of difficulty in forecasting future short-term rates at a given maturity horizon. A relatively strong correlation between the term premium and the present and expected interest rate levels lent some support to the theoretical assumption. Generally speaking, when interest rates are low, their volatility is also low. This enables investors to make better forecasts and demand a lower term premium. Although the presented long-term correlation patterns of the term premium and the risk-neutral yield are similar, it should be noted that their short-term movements differ significantly. For instance, in case of the 10-year GB, the volatility of the term premium was lower than the volatility of the risk-neutral yields. Additionally, whereas the largest decrease of the risk-neutral yield was observed over the years 2011-2012, the term premium decreased only slightly in this period. Instead, the largest drop of the term premium appeared in between end of 2013 and half of 2015, when the uncertainty about the future monetary policy rate movements was suppressed by the introduction of an unconventional monetary policy tool.

The credit risk premium should be correlated with investor perceptions about Czech government bond credit risk. Given the method for estimating the credit risk premium, the correlation between it and CDS spreads was very high (even with CDS spreads of other maturities; see Table 4.1). Another market indicator of credit risk—the spread between Czech and German five-year GB yields—was also highly correlated with the credit risk premium. The credit risk premium turned out to be closely correlated with GDP growth and exchange rate and market uncertainty indicators (see Table 4.1). Worsening economic performance and a weakening Czech koruna could signal potential macroeconomic instability and require foreign investors to monitor more closely the fiscal position of the government. Global uncertainty as measured by the VIX index was also significantly correlated with the credit risk premium. When uncertainty rises, investors become more cautious and require higher compensation for bearing credit risk; sometimes this surge in credit premium is not fully justified by the development of Czech fundamentals.

The portfolio effect should theoretically be linked with investors' preference for Czech GBs over other assets —denominated in korunas or other currencies. The inflow of short-term foreign assets into the Czech economy and the proportion of Czech GBs held by non-residents were strongly correlated with the portfolio effect when we correlated their levels. A strong level correlation was also found between the portfolio effect and the currency-hedged profit on investing in Czech assets. Rising yields on this type of investment were associated with a lower portfolio effect. These correlations can be interpreted as meaning that an inflow of foreign portfolio investment motivated by hedged profits boosted demand for Czech GBs as an attractive instrument, causing their yields to turn negative. Czech GB trading volume itself was not significantly correlated with the portfolio effect.

4.4 Czech GB Yield Curve Response Analysis

In this section, we estimate a Bayesian vector autoregression model with an exogenous variable (BVARX) model of the Czech economy to obtain some basic responses of Czech government bond yield curve to macroeconomic shocks. In particular, we focus on shocks to expectations, which allows to evaluate the extent to which the yield curve can be considered as a forward-looking indicator of the business cycle. Using the presented decomposition methodology, we split the yield curve responses into the responses of individual components. This allows us to interpret the yield curve movements in a greater detail and obtain insight into monetary policy transmission. The aim of the presented analysis is to illustrate the usefulness of the decomposition in relation to the interpretation of macroeconomic dynamics. The development of more sophisticated macroeconomic VAR models is left for future research. The model can be written in the following form:

$$V_t = A_0 + A_1 V_{t-1} + A_2 W_t + \epsilon_t \ . \tag{4.10}$$

V_t is a vector of endogenous variables, W_t is a vector of exogenous variables, A_0, A_1 and A_2 are parameter matrices and ϵ_t is a *i.i.d.* vector of random disturbances. In the presented model, we use seven endogenous variables and a single exogenous variable, i.e., the matrices A_0, A_1 and A_2 have dimensions 7×1, 7×7 and 7×1, respectively.

The seven endogenous variables include two macroeconomic variables, three IRS latent factors and the level and slope of the ASWS. ASWS represents the difference between the Czech GB yield and the IRS rates, which means that it equals the sum of the credit risk premium and the portfolio effect. The reason why we use the ASWS instead of its two components is to keep the model parsimonious. Additionally, the separation CDS quotations. Modeling them jointly therefore allows use of a longer sample period. Nevertheless, we also evaluate the results from the shorter sample period with these two components kept separate to obtain additional insight into the dynamics of ASWS responses.

The two macroeconomic variables in the model are forward-looking Consensus Forecasts of growth of GDP and Consumer prices (Consensus Economics 2018). Since the Czech yield curve comprises maturities up to 15 years, we prefer using long-term forecasts (forecasts of average annual growth rates 5-10 years ahead). However, the long-term forecasts are published only with a 6-month periodicity. Therefore, to introduce sufficient monthly variability of the forecasts, we obtain the series as a weighted average of the interpolated long-term forecasts and 1Y forecasts. In a baseline estimation, the weights were arbitrarily set to 80% for long-term forecasts and 20% for 1Y forecasts, which puts most emphasis on the long-term trends. However, below, we also show results for alternative weights.

Unlike a canonical monetary VAR (Bernanke & Blinder 1992, for instance), we do not use the monetary policy rate, since the monetary policy rate hit its lower bound during the sample period. As a result, the monetary authority used the exchange rate intervention as an alternative tool, which can be considered a structural change. Including monetary policy or money market rates would consequently lead to biased results. Instead, we evaluate the effect of the shadow rate, which we calculate from the three IRS latent factors X_t extracted from the estimated affine model (SR-SGA model specification, see Section 4.2). This means that by including the three IRS latent factors into the BVARX model, we allow both an unbiased monetary policy proxy (the shadow short rate) and the interest rates to enter the model. The shadow-rate specification of the affine model avoids the bias caused by the lower bound. The shadow short rate can be easily obtained in the SR-SGA model as a sum of the latent factors X_t (plus the α_0 parameter from (4.3)). This shadow short rate can be seen as a proxy for overall monetary policy conduct, reflecting both interest rate tools and any unconventional tools (Krippner 2015). Further, the estimated affine model also allows us to translate responses of the latent factors X_t to responses of the rates via equation (4.6) and to decompose these responses to the two components: the risk-neutral yield and the term premium.

To be able to infer the responses of the Czech GB yield curve to macroeconomic shocks, we need to introduce another two components: the credit-risk premium and the portfolio effect. These are jointly expressed by the ASWS. Using the first two elements of the Nelson-Siegel function fitted over ASWS, we represent the ASWS term structure by two variables: its level and its slope. These enter the

BVARX model as the sixth and the seventh variables. As noted before, to obtain additional insight, a model with shorter sample period and separated credit risk premium and portfolio effect is also estimated and discussed below. The results of this alternative estimation might however be biased by the shortened period covering only the low-yield environment.

Apart from endogenous variables, we also consider the effect of general market uncertainty on the Czech GB yield curve. We assume these effects come from global financial markets; hence we use the VIX index as a proxy. Since the Czech economic situation has a negligible effect on the global markets, we do not assume any feedback loops, which supports the exogeneity of this variable.

To identify the model, we utilize recursive identification with Choleski decomposition. In this case, ordering of the endogenous variables is crucial. We order them as they are described above. Ordering macroeconomic variables first is reasonable because of the lag in their publication and an overall sluggish response of the real economy to financial shocks. The IRS factors are ordered afterwards, since we assume that they react immediately to shocks to the macroeconomic variables but not to shocks to ASWS. Finally, the ASWS factors are ordered at the end.

We use three lags for the BVARX model. The Akaike information criterion for the VARX model hints that at least two lags should be used (see Figure C.4). Although the criteria reach their minimum for two lags, we use three lags which is more common in the macroeconomic literature (the difference between the Akaike information criterion for two and three lags is small). To support robustness, we provide comparison of results for various numbers of lags in the Appendix.

For estimation, we use the sample period identical to the rest of the paper, i.e., 177 months from July 2003 until March 2018. We use flat priors and obtain the final distributions of parameters and impulse-response functions using Gibbs sampling.[10] The use of flat priors has its negative effects, especially for forecasting performance, which we do not evaluate (Giannone *et al.* 2015). However, the aim of the presented BVARX analysis is to highlight and further support the interpretation of the obtained components. A complex analysis of the optimal BVARX specification, prior selection and evaluation of the forecasting performance is beyond the scope of this paper and we leave it for future research.

To discuss the results of the model, we mainly focus on the impulse-response functions. In our calculation we proceed in three steps. First, from the model

[10]In the Gibbs recursion, we use 5,000 iterations, of which the first 2,000 iterations are discarded.

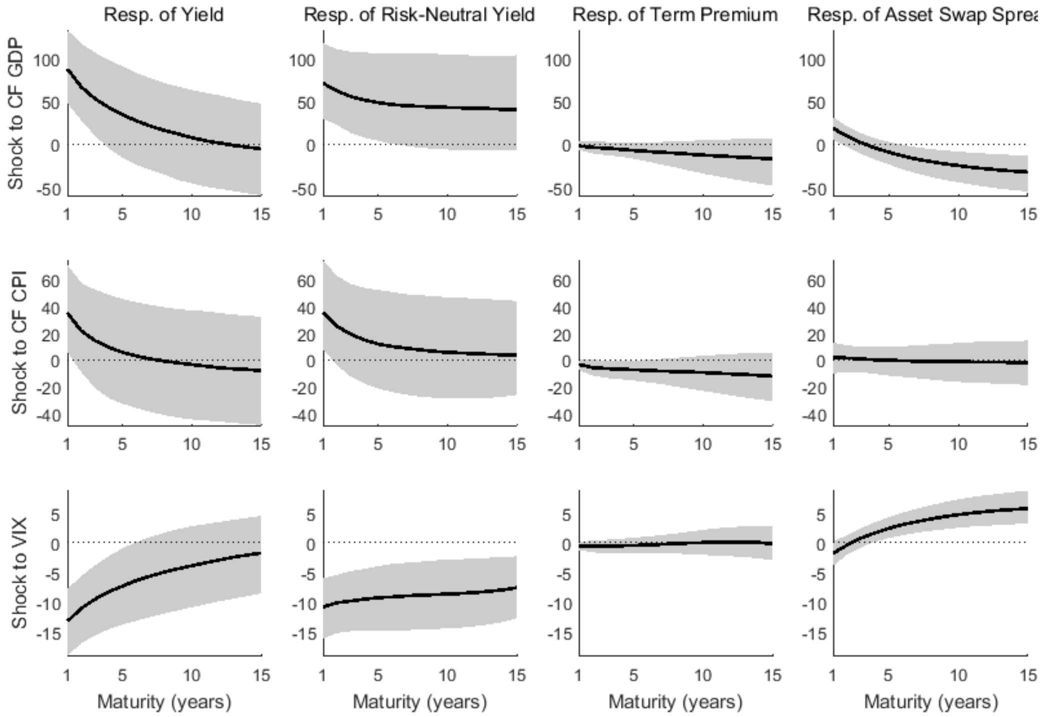
parameters from each Gibbs iteration, we calculate responses of the yield factors (three IRS factors and the level and the slope of ASWS) to shocks in the macro-financial variables (Consensus Forecasts of growth of GDP and CPI and the exogenous VIX index) over a 4-year horizon. Afterwards, we translate the responses of the yield factors to responses of the yield components. That means that (i) from IRS factors' responses, the responses of the risk-neutral yield and the term premium are calculated; and (ii) from the responses of ASWS level and slope, ASWS responses are calculated. ASWS responses aggregate the response of the other two components—the credit risk premium and the portfolio effect. Finally, we sum up the response of the risk-neutral yield, the term premium and ASWS to obtain the response of the Czech GB yield curve in the particular iteration.

Figure 4.8 shows the responses of the whole yield curve (in basis points) after 12 months from the initial shocks. The left column of the figure shows the response of the whole yield curve, which equals to the sum of responses of the components in the other columns. Each row presents a response to a shock in the variable denoted at the left of the figure. Figure 4.9 shows the dynamics of the response for the 5-year Czech GB yield over the 4-year horizon. In the figures, the solid line shows the median response, whereas the grey area displays 80% credible intervals of the responses.

We put the shocks to forecasted growth in GDP and CPI equal to the average absolute annual change of the series, which means 0.32 pp in case of GDP and 0.22 pp in case of CPI. In the case of VIX, it enters the model in a logarithmic form; we set the size of the shock equivalent to a growth of the VIX index from 12 points (the historical level related to low risk) to 30 points (the average value achieved in periods with an increased uncertainty).

As Figure 4.8 shows, the response of the Czech GB yield curve has various shapes, including both parallel shift and rotation. In response to a positive shock to the expected GDP growth rate, the yields increase in line with the growth of the risk-neutral yields. Simultaneously, the positive economic growth prospects slightly decrease the premium of uncertainty (reflected by the term premium) and lead to a decrease of slope of the ASWS. This can be explained by a decline in credit risk and portfolio reallocation towards longer maturities in case of positive economic news. As a result, the increase of yields of long maturities caused by the risk-neutral expectations is compensated by the effect of the other components. The yield curve therefore flattens.

Figure 4.8: Response of the whole yield curve after 12 months (in bps)

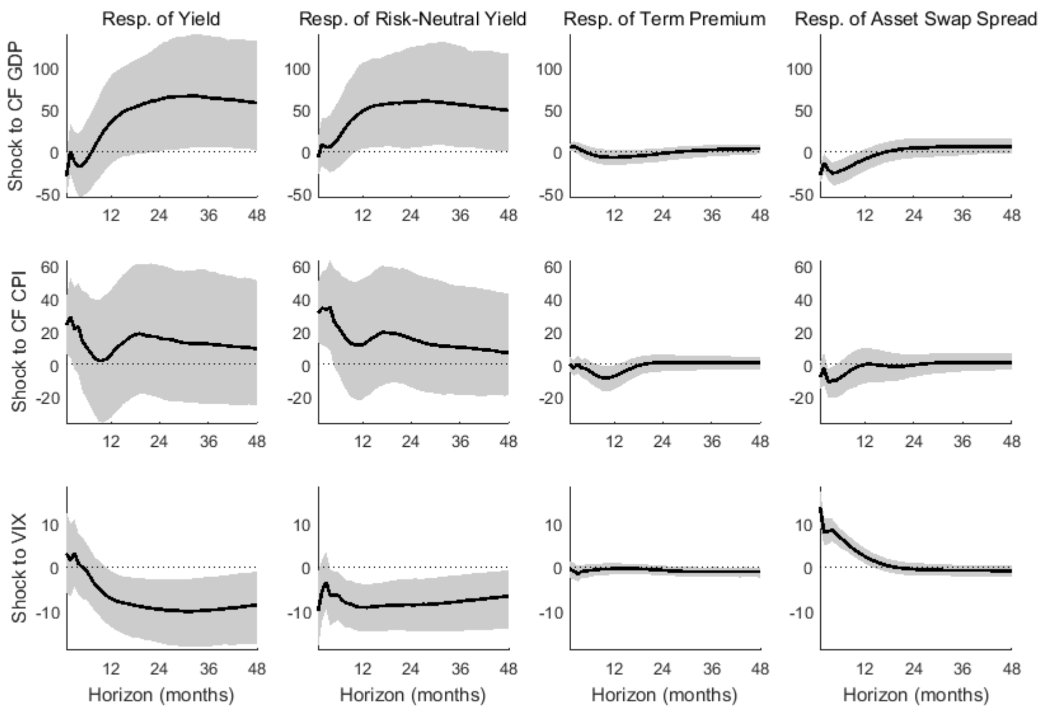


Note that the figure displays the response of the whole Czech GB yield curve (1–15 years) to the shocks after 12 months. The shocks are defined as a 0.32pp increase of forecasted GDP growth, 0.22pp increase of forecasted inflation and as an increase of VIX index from 12 to 30 points. The line displays the estimated response; the grey area displays 80% credible intervals.

A positive shock to expected inflation similarly leads to an increase in risk-neutral yields, although of a lesser magnitude. Unlike a shock to GDP, in this case, the shock causes a yield curve upward shift together with rotation. Such a response is triggered by the risk-neutral yield, i.e., the expectation of a reaction from the monetary authority, which translates into the adjusted expected future short rate path. The response reaches its maximum around 60bps, 6 months after the shock for short maturities, whereas for the longer maturities, the response is smaller but quite persistent (see Figure 4.9). The term premium slightly rises for long maturities, which may reflect uncertainty about the new short rate path.

In the case of both economic shocks, the increase in the long yields due to a change in the risk-neutral yield is compensated by other effects. The results here presented need to be cautiously interpreted in the context of the sample period: most of the sample covers the period following the global financial crisis, which was specific in terms of the non-standard monetary policy conduct and persistent low-yield environment. We interpret the results as showing that

Figure 4.9: Response of 5Y yield, at horizon up to 4 years (in bps)



Note that the figure displays the dynamics of the response of the 5-year Czech GB yield to shocks over a 48 month response horizon. See note to Figure 8 for the description of the plot elements.

positive expectation shocks regarding the real economy, and price inflation, lead to an increase of yields, although compensated by specific factors for long maturities. Such an interpretation is in line with the latest empirical evidence from the years 2016–2017: the expected monetary policy tightening, which was triggered by the positive inflation data since the end of 2016, was not fully reflected by the long end of the yield curve. The whole yield curve was at that time pushed down by an increase in the demand for Czech GBs following foreign speculation on Czech koruna appreciation. A similar compensation of responses was also present after the negative GDP shock during the crisis. The shock led to a drop in short yields, but the long yields were kept high due to increased risk pricing and capital outflows.

The persistence of the shocks is high (see Figure 4.9). This could imply a predictability of yields in the Czech GB market and limited efficiency of the market and therefore cast doubt regarding the validity of the affine model. The persistence however needs to be considered in terms of uncertainty: the response of monetary policy to economic shocks is uncertain in terms of both timing and extent. Therefore, the gradual response of yields reflects the gradual monetary policy response. Furthermore, the sample period includes the global financial crisis which represents a highly persistent real shock—yields of long maturities decreased for several periods after the initial shock (see Figure 4.2). The new low-yield environment following the crisis could be seen as a structural shock, which the model does not incorporate and therefore interprets the transition towards new normal as a sluggish response. Future possible extensions of the presented framework could include regime shifting, which would partially correct this issue.

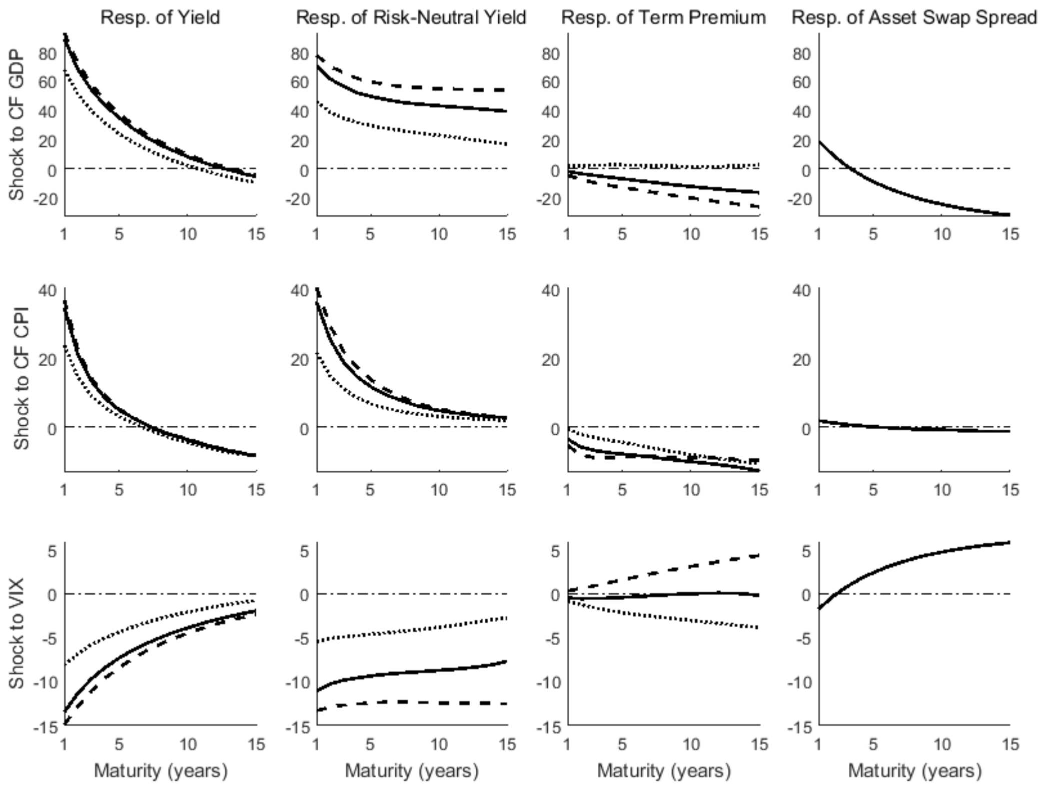
Finally, the exogenous shock to VIX, representing a shock towards increased market uncertainty, rotates the yield curve by pushing the low end of the yield curve downwards. In absolute terms, the response is lower than in case of the shocks to the real economy. The response is a result of two opposing effects. The shock has a negative impact on the expected monetary policy rate path, i.e., the risk-neutral yields of all maturities decrease (Figure 4.8). On the other hand, it increases the risk premium of Czech GBs and reduces their attractiveness to investors, which pushes the ASWS up for long maturities. As a result, the yield curve rotates. However, the response changes over time: for the 5-year yield, the effect of the ASWS prevails for the first 6 months; afterwards, the effect of decreased monetary policy rate expectations becomes dominant (see Figure 4.9).

The outflow of investors (presumably foreign), which causes the ASWS to increase after increased market uncertainty, signals that their perception of the Czech GB bonds as a safe asset is limited. The role of foreign investors in determining the ASWS is dominant due to the high turnover these investors have in the Czech GB bond market, relative to domestic investors (CNB 2014). Also, in this case the results reflect the beginning of the Global financial crisis, when global financial market uncertainty and its effect on the real economy was one of the reasons for the global yields decreasing towards record-low levels. Similarly, during the subsequent gradual global process of return towards non-zero yields, events triggering market uncertainty (the August 2015 Asian market crash or the Brexit vote, for example) further postponed the expected monetary policy tightening.

The results demonstrate that the response of the yield curve is truly complex and that movements of the components may mutually offset. The drop of the term and credit premia and the response of the portfolio component after a positive economic shock may have important implications for both the monetary and financial stability policies of the CNB. Similarly, the combination of macroeconomic and financial responses to the market uncertainty shock (VIX) needs to be accounted for when considering possible policy measures.

To measure the effect of the lower bound on responses of the yield curve, the steady state of the VAR analysis is shifted towards the lower bound. In the alternative setup, we set the steady state of yields equal to average factor values before/after the recent global financial crisis. Due to the non-linearity of the $F(X_t, \tau)$ function in case of the shadow-rate model, the steady state level matters for the yield responses within the VAR analysis (except for the ASWS, which does not enter the affine model). After doing so, the responses to the impulses are altered (see Figure 4.10).

Figure 4.10: Responses at the lower bound (in bps)



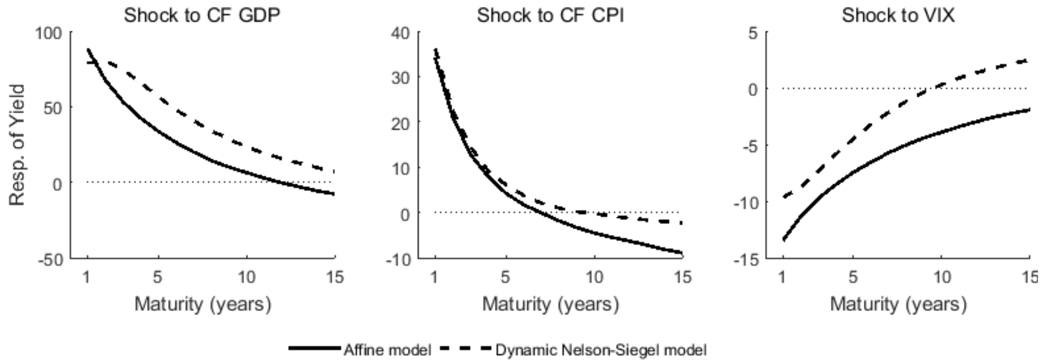
Note that the figure displays the dynamics of the response of the yield curve under various steady states at the 12-month horizon. See note to Figure 8 for the description of the plot elements.

In general, the lower bound suppresses the responses. This is caused by the lesser reaction of the monetary authority at the lower bound in terms of interest rate adjustment. Technically, following the concept of the shadow rates, the shadow rate response translates to only limited observed rate response where rates are close to their lower bound (see Figure 4.4 and Figure 4.5). Economically, this can be explained by the presence of unconventional monetary policy tools. In the case of the monetary policy response, it can be expected that unconventional policies will be altered first, creating a buffer against the monetary policy rate change. In practice, such a situation was present in the Czech monetary policy during the exchange rate commitment regime: the commitment needed to be abandoned before changing the policy rates. One interesting finding was that the pre-crisis and low-yields response of the term premium are exactly opposite after a shock to VIX. This is however not surprising: before the crisis, a shift in financial market uncertainty raised questions about the possible monetary policy response, which was in line with growth in the term premia. In contrast, since the crisis, VIX shock meant extending the low yield regime, i.e., decreasing the uncertainty about monetary policy steps in the near term.

Finally, we also present several sensitivity analyses which provide additional insight into the presented results. First, we re-estimate the BVARX model using the DNS approach. That means that we estimate the DNS model and gather the factors - the level, the slope and the curvature. Afterwards, we estimate the BVARX model using these three factors. From the estimated responses of factors, the yields are calculated using the Nelson & Siegel (1987) function. As the results show (see Figure 4.10), the responses in both DNS and affine models are roughly similar. This supports the robustness of our results. However, the DNS framework does not allow us to decompose the yields. Therefore, sticking to DNS framework would lead to a conclusion that the response of yields of long maturities are insignificant without the knowledge of mutually offsetting components, which was presented above.

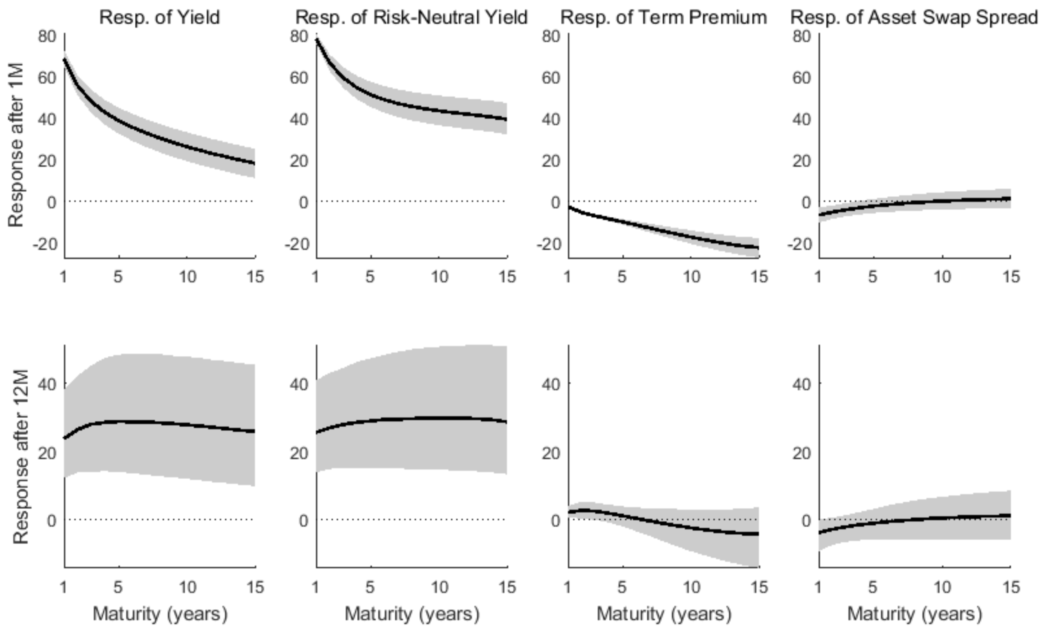
Second, we also show the effect of monetary policy. Since we use a shadow-rate model, we utilize the shadow rate as a monetary policy proxy. It can be obtained as a sum of the three affine yield factors. The response of yields after a 1pp increase in the shadow rate is first almost proportional for the shortest maturities and gradually decreases over time (see Figure 4.12). For the longer maturities, the response of yields is only partial but still significant. The less than proportional response may be explained by a mix of (i) the opposite effect of decreasing term premium, (ii) the one-off definition of the shock (vs. construction of the yields of long maturities as average value over the full horizon) and (iii) the option effect embedded in the shadow rate, which matters close to the lower bound.

Figure 4.11: Response in comparison with Dynamic Nelson-Siegel framework results (in bps)



Note that the figure displays the response of the whole Czech GB yield curve (1-15 years) to shocks after 12 months. See note to Figure 8 for the description of the plot elements.

Figure 4.12: Responses to the monetary policy shock (in bps)



Note that the figure displays the response of the whole Czech GB yield curve (1-15 years) to the 1pp increase in the shadow rate after 12 months. The line displays the estimated response; the grey area displays 80% credible intervals.

Finally, we provide additional sensitivity checks. We evaluate various shares of long-term forecasts when constructing the CF GDP and CF CPI series (see description above). The results show (see Figure C.5) that the shape of the responses is preserved. However, by increasing the share of long-term forecasts, the response increases in its magnitude.[11] This reflects the empiric ability of

[11]The different response of the series consisting of 100% long-term forecasts is given by the

the yield curve to reflect changes in expectations rather than realized shocks. In an additional sensitivity check, we show that the results are stable across a varying number of lags in the BVARX model (see Figure C.6). The last sensitivity check shows that the results for the macroeconomic variables are preserved also when the ASWS factors are excluded from the model. This means that the BVARX is estimated for the CZK IRS rates rather than the Czech GB yields. The results show (see Figure C.7) that the basic direction of response to macroeconomic shocks is preserved, although the extent of the response differs for some maturities. Exclusion of ASWS might lead to an omitted variable bias; we therefore argue for keeping it in the baseline estimation.

4.5 Conclusion

The yield curve is an important indicator of the economic cycle, as it aggregates the expectations of market participants. The factors that affect the shape of the yield curve do so to different extents in different circumstances. To interpret the evolution of the yield curve correctly, it is therefore useful to decompose it. This article presented a method to decompose the Czech government bond yield curve.

We decomposed the Czech GB yield curve into four components: a risk-neutral yield, a term premium, a credit risk premium and a portfolio effect. The first two were obtained by decomposing the zero-coupon koruna IRS curve using a SR-SGA model. The credit risk premium was estimated from CDS quotations for Czech GBs. The portfolio effect formed the residual. Inclusion of a credit risk premium and a portfolio effect improve the understanding of the dynamics of interest rate. These two additional components are necessary for government bonds in which investors see a non-zero default risk.

A comparison of the four estimated components with selected macroeconomic and financial variables confirmed the strong theoretical interpretation of these components. As the theory had anticipated, for example, the risk-neutral yield matched analysts' expectations about future short-term policy rates, and the portfolio effect became highly negative as the removal of the CNB's exchange rate floor neared.

interpolation. The absence of any short-term forecasts in the calculation results in biased behaviour - therefore, we utilize an 80% share of long-term forecasts in our baseline estimation as an optimal combination of high share of long-term forecasts while still allowing for short-term variability.

The above decomposition allowed for a more detailed interpretation of the responses of the Czech GB yield curve to macroeconomic and financial shocks. Using a vector autoregression analysis, we show that the yield curve responds both by changing its level and by rotation. Such responses result from a combination of various responses of the yield components to the shocks. Most importantly, the upward response of yields following positive shocks to expectations about GDP and CPI is partially compensated by shifts in portfolio allocation and risk pricing. Such a finding is in line with international experience (Greenspan's conundrum in the U.S. in 2005–7) and has important implications for both monetary policy conduct and the usage of the yield curve as an indicator of the business cycle. Also, a rise in global risk awareness proxied by VIX leads to a rise in yields via the portfolio effect, which suggests that Czech government bonds do not possess a status of a safe haven asset. Finally, at the lower bound, we show that the yield response is generally suppressed, which is in line with economic reality.

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Appendix A

Appendix to Chapter 2

A.1 News Database Filtering

To obtain the headlines that provide sufficient information about U.S. Treasury yield curve movements and their sources, we apply a sequential approach:

1. We filter news articles from News Monitor from Refinitiv EIKON that
   (i) include at least one of the terms U.S. / United States,
   (ii) at least one of the terms Treasury / Yield / Bond / Bill / Note,
   (iii) and at least one of the terms rise / grow / increase / advance / gain / rise / jump / decrease / plummet / decline / shrink / drop / deteriorate / lower / slump
   (or their variations).

2. We gather the headlines and identify certain linking words that divide the part of the headline describing the direction of the movement from the part discussing the cause (for example, the word "after" in the headline *U.S. yields plummet after Draghi comments; Fed decision ahead*).

3. In one of the parts of the headline, we identify keywords that inform about the direction (see step 1; we carefully divide cases where the headline mentions bond prices or yields, as these imply inverse movements). This defines the sign of the innovation.

4. In the remaining part of the headline, we identify the keyword that allows us to place the news headline into one or more of the five categories.

The lists of keywords to identify the categories were set as follows:

Fiscal policy: ' suppl'; ' auction'; '-suppl'; '-auction'; ' buyback'; 'notes sale'; 'note sale'; 'debt sales'; 'deficit'; 'refunding'; 'u.s. debt'; 'new debt'; '-year sale'; 'tips sale'

Fed surprise: ' fed'; ' bernanke'; ' yellen'; ' powell'; ' greenspan'; '-fed'; '-bernanke'; '-yellen'; '-powell'; '-greenspan'; ' rate'; '-rate'; ' fomc'; 'fomc '; 'tightening'; 'easing'; 'banker comments'; 'trichet'; 'fisher'; 'tapering'; 'stimulus'; 'draghi'

Macro news: ' cpi'; '-cpi'; ' job'; '-job'; 'sales data'; 'home sales'; 'retail sales'; 'confiden'; ' labor'; 'housing'; 'economic data'; 'weak data'; 'strong data'; 'durables'; 'u.s. outlook'; ' ppi'; ' napm'; 'ahead of data'; 'manufacturing'; 'productivity'; 'u.s. data'; 'tepid growth'; 'gdp'; 'consumer'; 'hopes for economy'; 'production'; 'trade report'; 'economic gloom'; 'recovery'; 'economic outlook'; 'wholesale'; 'durable goods'; 'recession'; 'home data'; 'growth rebounds'; 'us growth'; ' pmi '; 'u.s. growth'; 'economy'; 'u.s. rise'; 'price index'; 'econ data'; 'michigan'; 'after data'; 'factory'; 'factories'; 'inflation'; 'chicago pmi'; 'ism services'; 'payroll'; 'on data'; 'economic report'; 'home market'; 'u of mich'; ' ism'; 'outlook and data'; 'retail'; 'business index'; 'ism '; 'layoff'; 'industry'; 'core sales'; 'ism survey'; 'shopper'; 'trade deficit'; 'await data'; 'employment'; 'sentiment data'; 'awaits data'; 'house data'; 'business condition'; 'lackulster data'; 'robust data'; 'growth worries'; 'mortgage selling'; 'u.s. output'; 'u.s. weakness'; 'mixed data'; 'claims data'; 'spending'; 'data flow'; 'price data'; 'goods orders'; 'home price'; 'producer price'; 'gloom'; 'homes plan'; 'industrial'; 'home builder'; 'trade data'; 'lukewarm data'; 'tepid data'; 'u.s. decline'; 'data miss'; 'output data'; 'business data'; 'disappointing data'; 'corporate'; 'home resales'; ' wage'; 'import'; 'export'

Financial market: 'profit'; ' stock'; 'stock '; 'stocks'; ' equit'; ' earning'; 'tech sector'; 'nasdaq'; ' enron'; 'book profit'; 'oil price'; ' oil'; 'oil-price'; 'sp 500'; 'fannie'; 'microsoft'; ' bull'; ' bear'; 'dividend'; 'wall st'; 'correction'; ' shares'; 'shares '; 'technicals'; 'technical support'; 'draw buyers'

Capital flight: 'safety'; 'flight to quality'; 'mideast'; 'warning'; ' global growth concerns'; 'argentin'; 'tragedy'; ' attack'; ' uncertain'; ' g7'; ' fear'; 'russia'; 'explosion'; 'iraq'; 'safe-haven'; 'war '; ' war'; 'nervous'; 'geopolitic'; 'blast'; 'hurricane'; ' rita '; 'global tension'; 'baghdad'; 'democrats'; 'saddam'; 'china'; ' alert'; 'u.s. troop'; ' vote'; 'subprime'; 'hungary'; 'bailout'; 'jitters'; 'rescue'; 'stress'; 'greece'; ' aig '; 'speculation crisis'; 'debt crisis'; 'debt concerns'; 'tension'; 'safehaven'; 'risk appetite'; 'global growth'; 'global slowdown'; 'demand for risk'; 'credit rating'; 'downgrade'; 'currency manipulat'; 'greek'; 'budget talks'; 'fiscal'; 'debt ceiling'; 'debt clock'; 'default'; 'ukraine'; 'middle east'; 'global economic'; 'ebola'; 'chinese'; 'riskier'; 'election'; 'trump'; 'syria'; 'brexit'; 'north korea'; 'global market'; ' irma'; 'budget plan'; 'tax'; 'shutdown'; 'sanctions'; 'italy'; 'borrowing'; 'mexico'; 'anxious'; 'tariff'

A.2 Descriptive Statistics and Correlations

Table A.1: Descriptive Statistics and Correlations

	Yield level		Difference of yield	
	1Y	10Y	1Y	10Y
Sample (common to all maturities)				
first observation	12/4/2000			
last observation	6/28/2019			
no. of observations	4,671			
Descriptive statistics (in % for level, in basis points for difference)				
maximum	5.911	5.837	40.47	26.33
	(12/4/2000)	(3/14/2002)	(9/19/2008)	(10/8/2008)
minimum	0.083	1.400	-54.41	-51.89
	(14/5/2014)	(7/8/2016)	(9/17/2001)	(3/18/2009)
mean	1.680	3.524	-0.086	-0.077
standard deviation	1.562	1.168	4.171	5.848
Pearson correlation coefficient (all observations)				
Fiscal policy			0.043	0.072
Fed surprise			0.099	0.139
Macro news			0.127	0.193
Financial market			0.119	0.142
Capital flight			0.073	0.120
Total			0.175	0.252
Pearson correlation coefficient (only observations including a news article)				
Fiscal policy			0.248	0.378
Fed surprise			0.298	0.480
Macro news			0.310	0.445
Financial market			0.301	0.466
Capital flight			0.220	0.439
Total			0.283	0.427
Point biserial correlation coefficient (only observations including a news article)				
Fiscal policy			0.284	0.418
Fed surprise			0.338	0.492
Macro news			0.337	0.448
Financial market			0.342	0.502
Capital flight			0.236	0.448
Total			0.327	0.467

Source: Fed (2019), News Monitor at EIKON – Refinitiv, author's calculations.
Note that the correlation coefficients are calculated between the first difference of yields and the triggers from news headlines (a dummy indicating a presence of a news article with a sign based on the headline). When including all observations, zeros are assigned to the dummies of news triggers for the days where no related article was present in the sample. This leads to relatively low correlations. After removing these observations, i.e., calculating the correlations only for days when a news article was published, the correlations increase.

A.3 The Largest Daily Movements

Table A.2: The Largest Daily Movements of the 10Y Yield (movements in bps)

year	movement	date	description of trigger	headlines on surrounding dates
2001	-17	01/02	Fed expectations	U.S. Treasury notes rise on hopes for lower rates.
2001	24	11/15	U.S. equity market, macro-data	U.S. Treasuries mixed after New York drop. U.S. T-bond extends gains to full point after CPI.
2002	-21	11/07	Fed meeting	All ingredients for rally in place: Cuts to U.S. rates, taxes: Bonds poised for a slump that will make stocks attractive
2002	23	11/27	Treasury auction, macro-data	U.S. Treasury yields rise ahead of auction, data.
2003	24	01/02	Macro-data, portfolio allocation (flight from safety)	Canadian dollar jumps on U.S data, bonds pummeled. Euro debt-Yields rise above 3-1/2 year lows after U.S. data. U.S. Treasuries drift lower as safety bid wanes.
2003	-18	08/06	Treasury auction	S&P 500, Dow, make gains: Telephone stocks rise, Treasuries rebound, but U.S. dollar sinks lower U.S. Treasury yields rise, five-year supply looms. U.S. stocks gain, aided by solid Treasury note sale. GLOBAL MARKETS-Shares, bonds rise after U.S. refunding ends.
2004	25	04/02	Macro-data	U.S. Treasuries plummet after rousing jobs data
2004	-20	06/15	Fed meeting	U.S. Treasuries jump as Fed soothes on rate rise.
2005	15	03/09	U.S. equity market, corporate sector news	GM struggles with debt load: Interest costs rise as bonds near junk status. General Motors had 44% of U.S. market in 1980; that is expected to fall to 24% within five years
2005	-14	08/31	Macro-data	U.S. Treasuries jump on contraction in Chicago PMI
2006	-11	06/02	Macro-data	RPT-Treasuries gain on weak U.S. data ahead of payroll
2006	11	11/03	Treasury auction, macro-data	U.S. bonds lower after payrolls, before auctions
2007	14	09/20	Fed meeting	U.S. Treasury balances at Fed lower on Sept 19 Hungarian forint firms significantly, bond yields drop after U.S. rate cut
2007	-18	11/26	Macro-data	U.S. yields slump on fresh housing fears BONDS MARKETPLACE by Bloomberg U.S. bonds higher after report shows new home sales at a 12-year low; yields decline
2008	26	10/08	Macro-data, U.S. equity market	EURO GOVT-Bonds pare gains after U.S. non-farm payrolls U.S. TREASURIES TRIM GAINS AFTER STOCKS CUT EARLY LOSSES
2008	-27	11/20	Macro-data	U.S. TREASURIES ADD SLIGHT GAINS AFTER WEEKLY JOBLESS CLAIMS JUMP TO HIGHEST SINCE JULY 1992 U.S. Treasuries hold gains after Philly Fed data
2009	-52	03/18	Fed meeting	GLOBAL MARKETS-U.S. stocks surge on Fed move, bond yields slump
2009	26	06/01	Treasury auction, macro-data, Fed expectations	Banks beat expectations, TSX jumps 250 points; Dow higher as U.S. bond auction attracts solid demand; home sales, durable goods orders rise FOREX-Dlr up on U.S. yield rise, rate expectations
2010	-19	06/04	Macro-data	TREASURIES-Bonds rally as U.S. payroll rise disappoints
2010	22	12/07	Macro-data	U.S. TREASURY OUTLOOK-After rebound, yields may still rise GLOBAL MARKETS-U.S. stocks, bond yields rise on recovery outlook
2011	-21	08/09	U.S. equity market, Foreign events (French banks holding Greece debt)	TREASURIES-U.S. 30-yr bond rises a point as stock futures fall TREASURIES-U.S. bonds gain on French bank safety fears
2011	21	10/27	Foreign events (Eurozone)	U.S. 30-YR BOND EXTENDS LOSS TO TWO POINTS AS STOCKS GAIN AFTER EURO ZONE DRAFT STATEMENT
2012	17	03/14	Fed statement	TREASURIES-U.S. bonds drop after upbeat Fed statement
2012	-15	04/06	Macro-data	U.S. TREASURIES PRICES ADD GAINS AFTER U.S. JOBLESS CLAIMS RISE MORE THAN EXPECTED IN LATEST WEEK
2013	23	07/05	Macro-data	GLOBAL MARKETS-Stocks, dollar rally, U.S. yields jump on jobs data
2013	-17	09/18	Fed meeting	U.S. mortgage bond prices rise after Fed leaves purchases alone Turkish bonds, lira make slight gains ahead of U.S. Fed meeting U.S. investors turn to more dealers as bond liquidity declines
2014	10	07/30	Treasury auction	DOLLAR RISES BRIEFLY ABOVE 103 YEN AS U.S. YIELDS EXTEND EARLIER RISE AFTER SOFT 7-YEAR TREASURIES AUCTION
2014	-11	10/01	Portfolio allocation	TREASURIES-U.S. longer-dated bond prices gain more on PIMCO outflows
2015	-16	06/29	Foreign events (Greece debt)	TREASURIES-U.S. bond prices rise on Greece concerns
2015	16	12/03	Fed statement, foreigin events (Eurozone - ECB decision)	TREASURIES-U.S. yields rise after ECB disappoints, Yellen speaks
2016	-17	06/24	Foreign events (Brexit)	TREASURIES-U.S. bond prices rise as early Brexit results show 'Leave' leads
2016	22	11/09	Politics (election)	GLOBAL MARKETS-U.S. stocks jump along with bond yields after Trump shock, peso falls
2017	10	03/01	Fed statement	GLOBAL MARKETS-Fed trumps Trump as dollar, U.S. Treasury yields jump
2017	-10	05/17	Macro-data	Global Stocks Fall After U.S. Rout as Bonds Gain: Markets Wrap TREASURIES-U.S. bond yields drop as CPI, retail sales data miss forecasts
2018	-15	05/29	Foreign events (Italy debt)	TREASURIES-U.S. 10-year yields post largest one-day drop since Brexit TREASURIES -U.S. yields rise as Italy worries ease, for now
2018	10	10/03	Fed statement	BUZZ-U.S. banks: Up on Fed's move to ease rules, rise in treasury yields
2019	-9	01/03	U.S. equity market, macro-data	The close: Stocks reverse early drop to end higher, Apple dives in post market on profit warning U.S. 10-year Treasury slips to 11-month low
2019	9	01/04	Macro-data, Fed statement	BUZZ-U.S. big banks: Rises as strong jobs report pushes yields higher UPDATE 1-Euro zone yields jump as Fed's Powell triggers U.S. Treasury selloff

Note that news headlines were obtained from News Monitor from Refinitiv EIKON.

A.4 Estimation Procedure

The estimation procedure utilizes Bayesian updating. The procedure is initialized at the mean of the prior distributions, with the initial state vector and its variance obtained as the mean values from the pre-sample (see Section A.5). The following steps are conducted in each iteration of the updating procedure:

Kalman Filter: Using the values of parameters from the previous iteration (or the initial values), we evaluate the likelihood of the parameters using the Kalman filter procedure.

Metropolis Hastings for innovations: The magnitude and location of the innovations $x_{c,t}$ are drawn using proposal densities. For the change in the location of the innovations, we draw a random integer from a Poisson distribution to obtain the number of days to shift the location. We set the distribution parameter $\lambda = 0.5$, i.e., on average, half of the candidate draws have the location shifted by at least one day. The direction of the shift is also determined randomly. For the magnitude, we draw from a log-normal distribution with both the log-mean and the log-standard deviation equal to one. Thereafter, again using the Kalman filter, we evaluate the likelihood of the model given the drawn innovations. For both the original and the drawn innovations, we evaluate their probability at the prior densities for both the location and the magnitude. We accept the draw if the ratio of prior probabilities (the drawn one over the original one) times the ratio of likelihoods is larger than a random draw from a (0,1) uniform distribution.

Sampling states: The obtained innovations, either the original or newly drawn, are used to draw the states of the state-space model, which represent the time-varying parameters. To do so, first, the Kalman filter is applied once again, and thereafter, the Carter & Kohn (1994) procedure is utilized to draw the states.

Drawing variance matrices: Having the innovations and states drawn, we draw the variance-covariance matrices of the random disturbances in the transition equation and of the measurement errors in the measurement equation from the inverse Wishart distribution.

A.5 Details on Priors

The priors in the model are of three kinds. First, the innovations are defined by priors about their location. The prior distribution of the location is specified as a normal distribution with the mean at the day of the publication of the headline and a standard deviation of three business days. This standard deviation was set using expert judgment, taking into account the overall density of news: with on average 2–3 headlines per week, using 3 business days ensures that the prior is not too strict and yet that the news articles do not excessively contaminate one another.

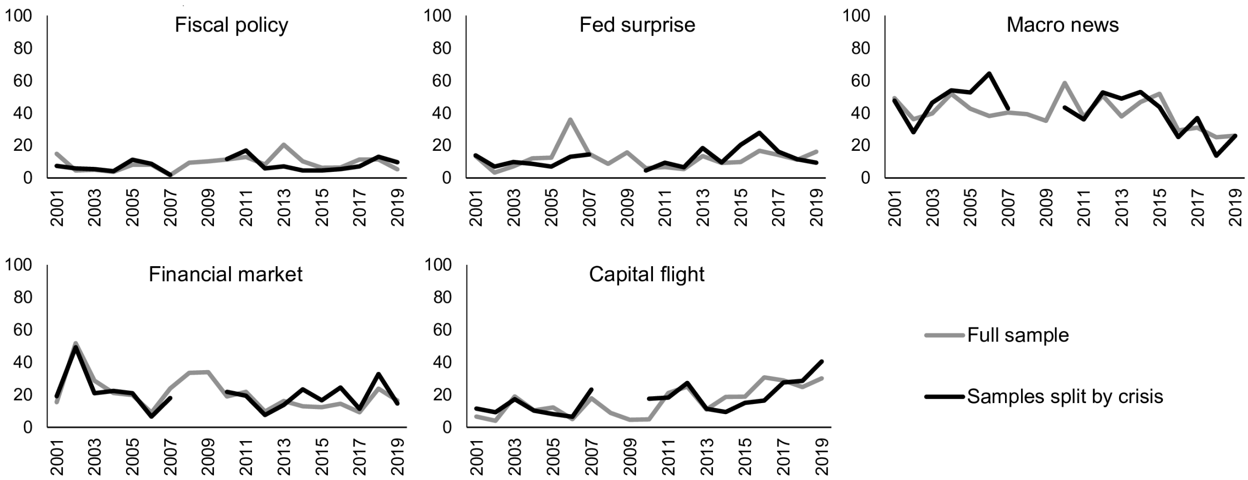
Second, innovations are further defined by priors about their magnitude. The log-normal distribution serves as a prior distribution of the magnitude of the innovation, which by the construction of the model needs to be positive (the signs are determined directly from the news headlines). The scale of the distribution may be freely chosen since the time-varying setup of the model ensures that the time-varying parameters adjust such that the observed yield variability is fitted properly. Therefore, we use log-normal(1,1) distribution, which has mode one, implying the common innovation as being of unit size.

Third, since the model assumes that the time-varying parameters follow a random walk, the only remaining parameters of the model are the variance-covariance matrices of random disturbances $\boldsymbol{Q}$ and of the measurement error $\boldsymbol{R}$. We choose the inverse Wishart distribution as the prior distribution for both variance-covariance matrices $\boldsymbol{Q}$ and $\boldsymbol{R}$. The choice of the inverse Wishart distribution is justified since the resulting conjugate prior distribution has many plausible properties (including a possibility to use several hyperparameters with a straightforward interpretation to describe the distribution; see Gelman *et al.* 2003, for instance).

We set the hyperparameters of the variance-covariance priors using a pre-sample. The pre-sample covers yields over the period 1985–2000. From these yields, we estimate yield factors (the level, slope and curvature) using the DNS model (Diebold & Li 2006). We set the prior for $\boldsymbol{R}$ from the measurement errors of the DNS model. The mean and variance of the first differences of the pre-sample factors are used as initial values for the states and their variance-covariance matrix. For each yield factor, there are five states: the series of time-varying regression coefficients for each news category. We set the initial values and $\boldsymbol{Q}$ priors identically for all categories. The prior for $\boldsymbol{Q}$ is obtained as this initial variance-covariance matrix multiplied by a small constant. We set this constant at the value 3.5e-04 in line with Cogley & Sargent (2005), which is common in the literature using a pre-sample to set the priors. In case of both variance-covariance matrices, the obtained hyperparameters imply only weakly informative priors. That is in line with our intention to set these priors so that they are not excessively informative, since we have no guidance on setting the prior parameters for the covariance matrices beyond the pre-sample data.

A.6 Robustness Check

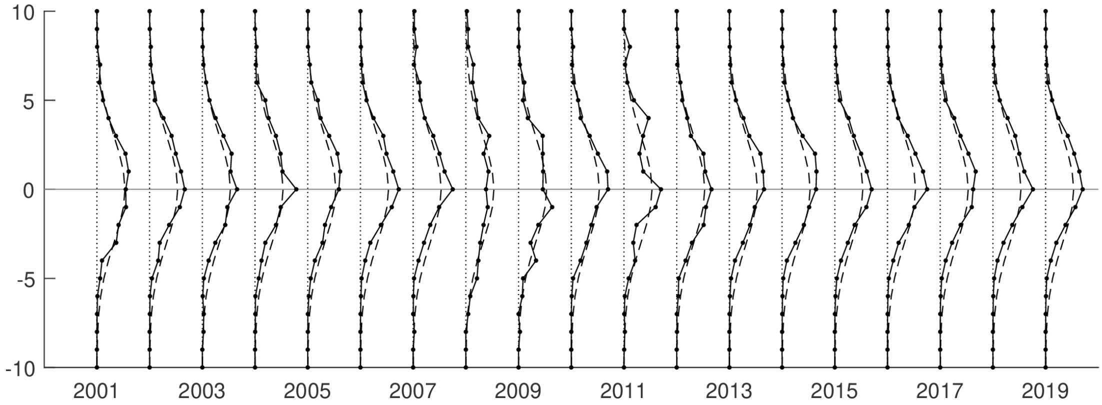
Figure A.1: Shares of Yield Movements, Ten Year (in %) – Robustness Check



Note that gray lines display the original full-sample estimate, whereas the black lines display the results after estimating the model separately on sub-samples split by the Great financial crisis. The shares of the five categories are calculated as an annual sum of absolute values of model-implied daily movements in the yield for the given category as a percentage share of the total annual sum of absolute values of model-implied daily movements.

A.7 Figures Depicting Estimated Parameters

Figure A.2: Posterior Distribution of Innovation Location
(difference from the day the news was published,
in business days, mean distribution for each year)



Note: The solid lines connect dots that illustrate the number of observations with a given difference in posterior location and the date the day was published. The dashed lines, identical for all years, represent the prior distribution of the location, i.e., a normal distribution with zero mean (located on the day of publication) and a standard deviation of three business days.

Figure A.3: Posterior Distribution of Innovation Magnitude: Aggregate Result
(x-axis: magnitude, y-axis: probability density)

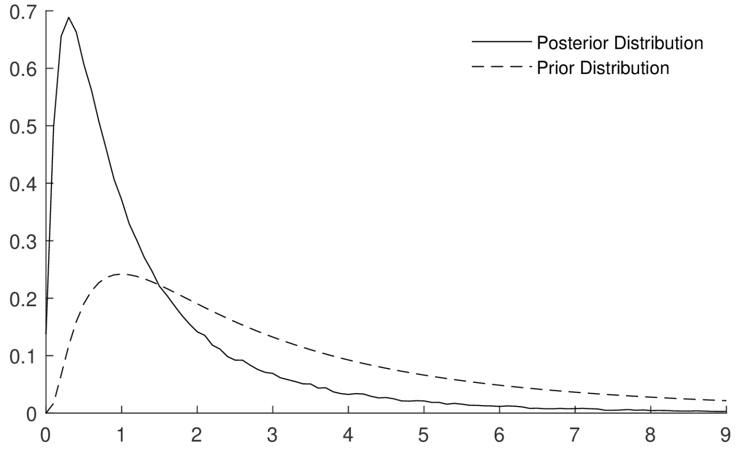
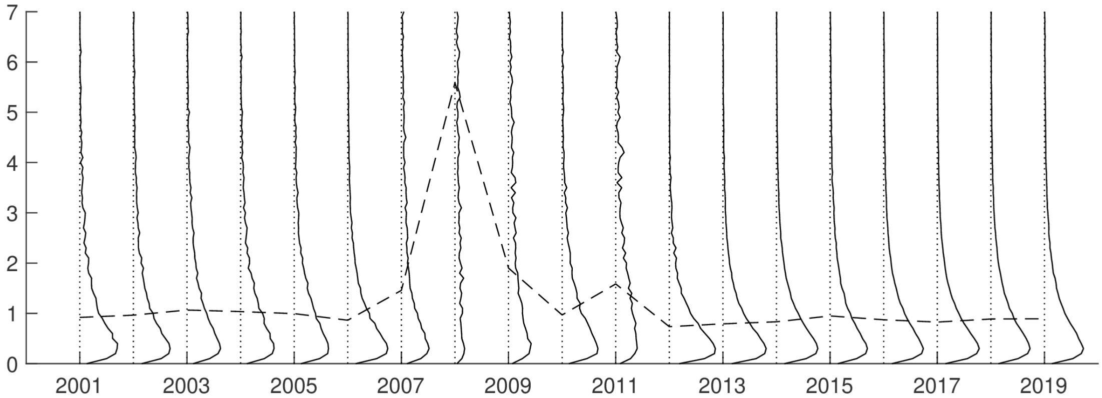
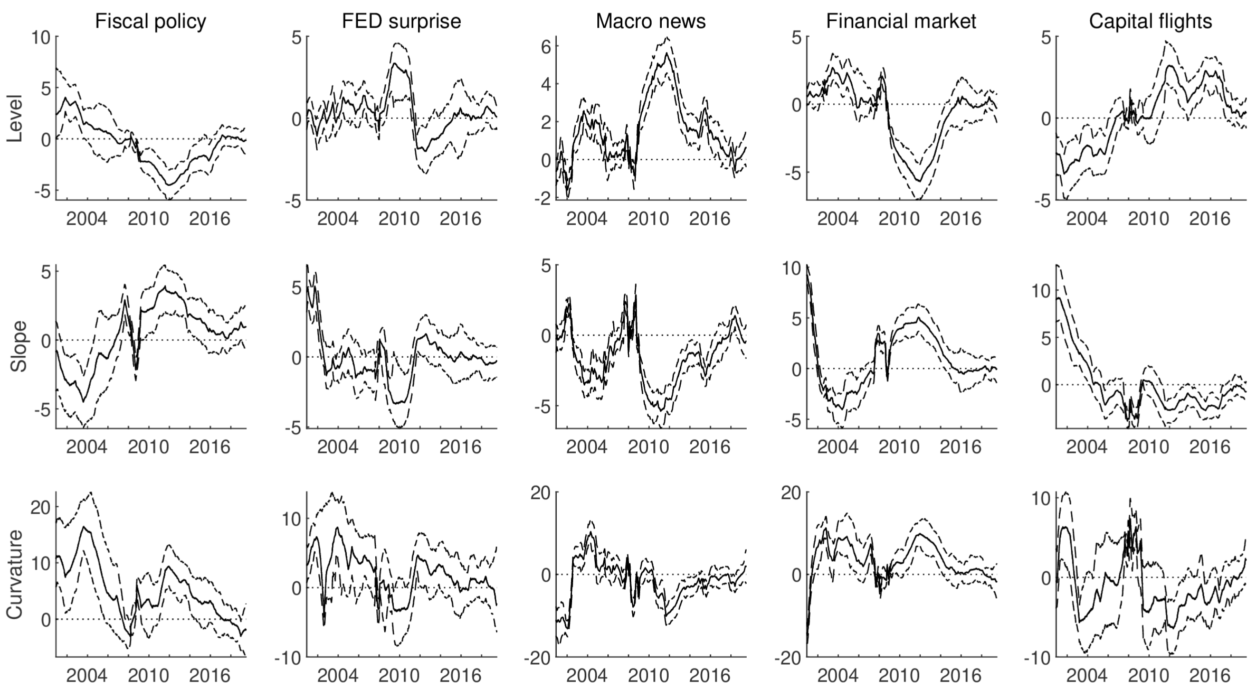


Figure A.4: Posterior Distribution of Innovation Magnitude: Dynamic View
(mean distribution for each year)



Note that the solid lines illustrate the average posterior distribution of the magnitude of the innovation calculated as a mean distribution for each year. The dashed line shows the mean posterior value (the mean of all posterior draws over the particular year).

Figure A.5: Posterior Time-Varying Parameters



Note that the solid lines illustrate the median posterior distribution, and the dashed lines show the 10% and 90% quantiles.

Appendix B

Appendix to Chapter 3

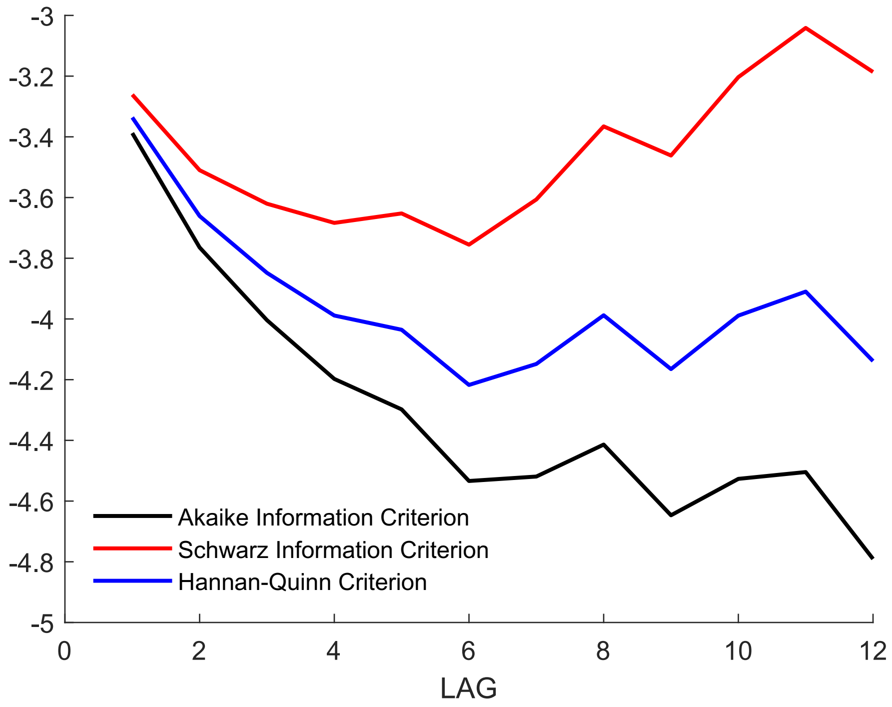
B.1 Estimated Parameters

Table B.1: Affine Model Parameters (selected)

Variable	mean	5% quantile	median	95% quantile
$\bar{F}$	0.000 -0.018 -0.018	0.000 -0.034 -0.052	0.000 -0.016 -0.015	0.000 -0.005 0.005
γ	1.000 1.557 1.813	1.000 1.321 1.462	1.000 1.554 1.820	1.000 1.786 2.117
σ_τ^2	0.0034	0030	0.0034	0.0038
Φ (the largest eigenvalue)	0.928	0.862	0.933	0.980
Φ^Q (the largest eigenvalue)	0.9984	0.9980	0.9984	0.9988
A (one-year yield)	0.0005	0.0004	0.0005	0.0006
A (ten-year yield)	0.0004	0.0004	0.0004	0.0004
B (one-year yield)	0.333 0.784 -0.118	0.325 0.772 -0.123	0.333 0.784 -0.118	0.340 0.796 -0.113
B (ten-year yield)	0.013 -0.064 1.049	0.012 -0.067 1.047	0.013 -0.064 1.049	0.014 -0.062 1.051

B.2 Information Criteria for SVAR-YLD Model

Figure B.1: VAR Model Information Criteria for SVAR-YLD Model



Appendix C

Appendix to Chapter 4

C.1 Estimated Values of Parameters

Note that small values of parameters and the lower bound reflect the fact that the model uses yields in decimal representation.

$$\widetilde{\kappa} = \begin{bmatrix} -0.01 & 0 & 0 \\ 0 & 0.13 & 0 \\ 0 & 0 & 1.03 \end{bmatrix}, \quad \widetilde{\lambda} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}, \quad \alpha_0 = 0.02, \quad \alpha_1 = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix},$$

$$\kappa = \begin{bmatrix} 0.002 & -11.62 & -0.15 \\ -0.001 & 10.94 & -0.002 \\ -0.051 & 6.93 & 65.43 \end{bmatrix} /10^2, \quad \lambda = \begin{bmatrix} 0.012 \\ 0 \\ -0.320 \end{bmatrix} /10^2,$$

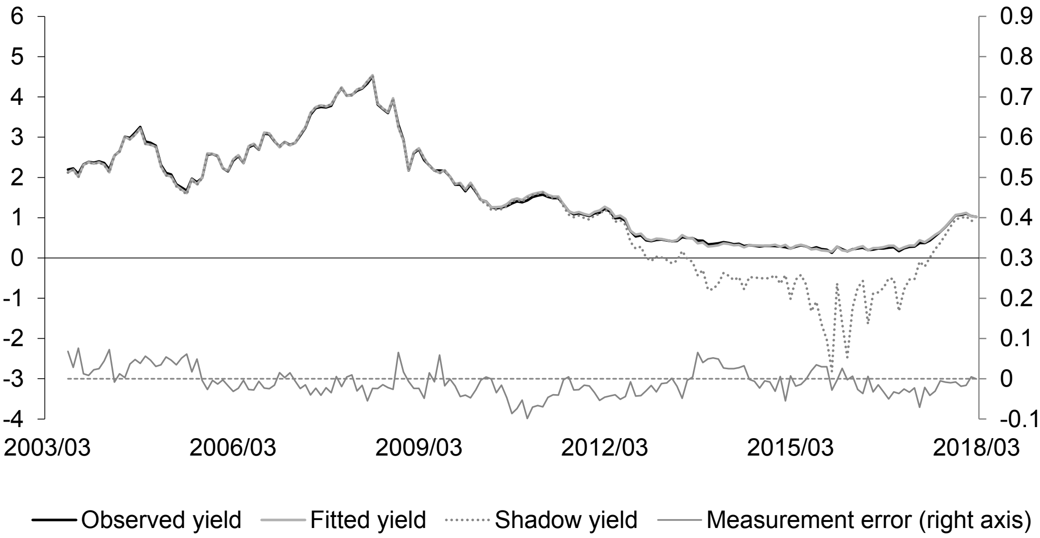
$$std(e_t) = diag(2.92, 2.98, 3.11, 3.18, 3.21, 3.24, 3.26, 3.28, 3.29, 3.30, 3.30, 3.30, 3.29, 3.28, 3.28)/10^4,$$

$$\sigma = \begin{bmatrix} 79 & 0 & 0 \\ -101 & 93 & 0 \\ 0.003 & 0.005 & 136 \end{bmatrix} /10^4 .$$

Lower bound value $= 0.0019$

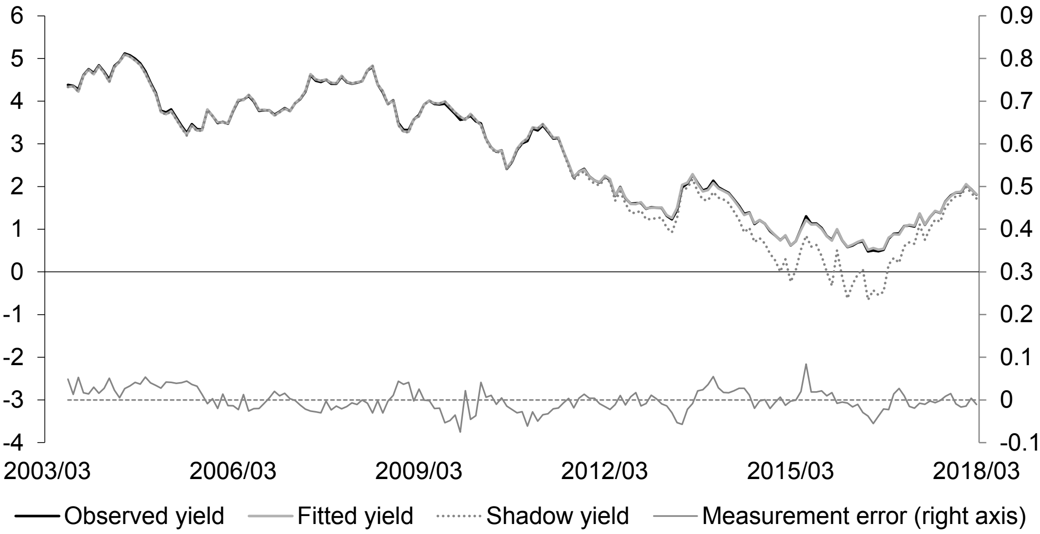
C.2 Additional Tables and Figures

Figure C.1: Affine model fit and shadow rate (one-year IRS, in %)



Source: Bloomberg, Prague Stock Exchange, MTS Czech Republic, Thomson Reuters, authors' calculations

Figure C.2: Affine model fit and shadow rate (ten-year IRS, in %)



Source: Bloomberg, Prague Stock Exchange, MTS Czech Republic, Thomson Reuters, authors' calculations

Figure C.3: Measurement error series (in bps)

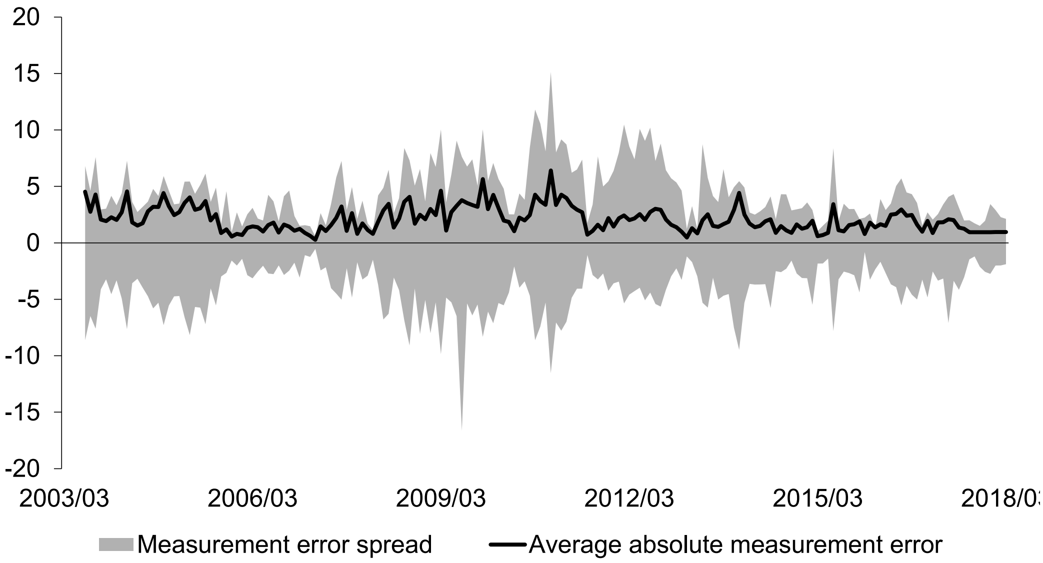


Table C.1: Measurement error diagnostics

Maturity		1Y	5Y	10Y	15Y
Normality (Shapiro-Wilk test)		YES	NO	YES	NO
Autocovariance (Ljung-Box)		YES	YES	YES	YES
Homoscedasticity (Ljung-Box on squares)		NO	NO	NO	YES
Cross-correlations (%):	1Y	100	-10	68	-71
	5Y	-10	100	-38	22
	10Y	68	-38	100	-86
	15Y	-71	22	-86	100

Note that the tests were evaluated for 5% significance level.

Figure C.4: Information criteria (criteria values, x-axis: lag)

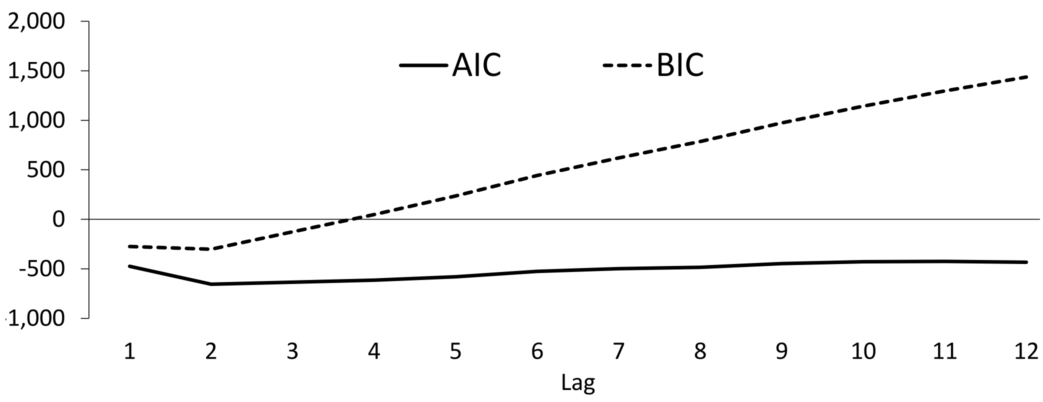
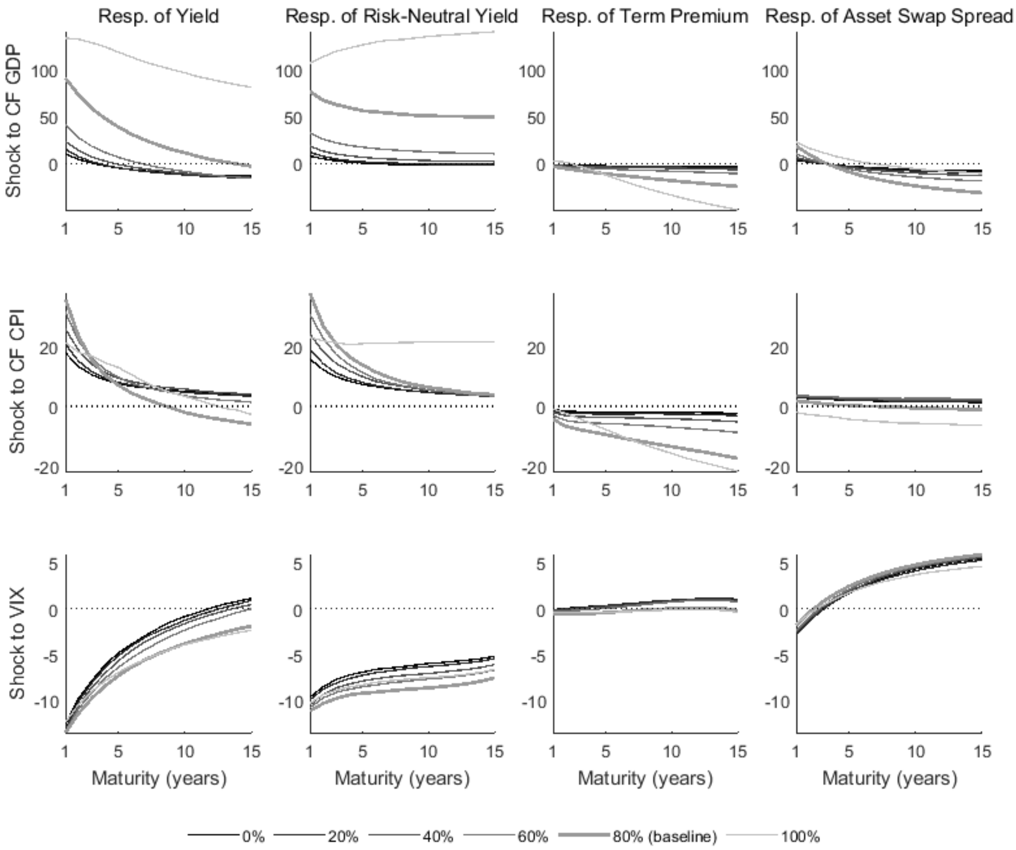
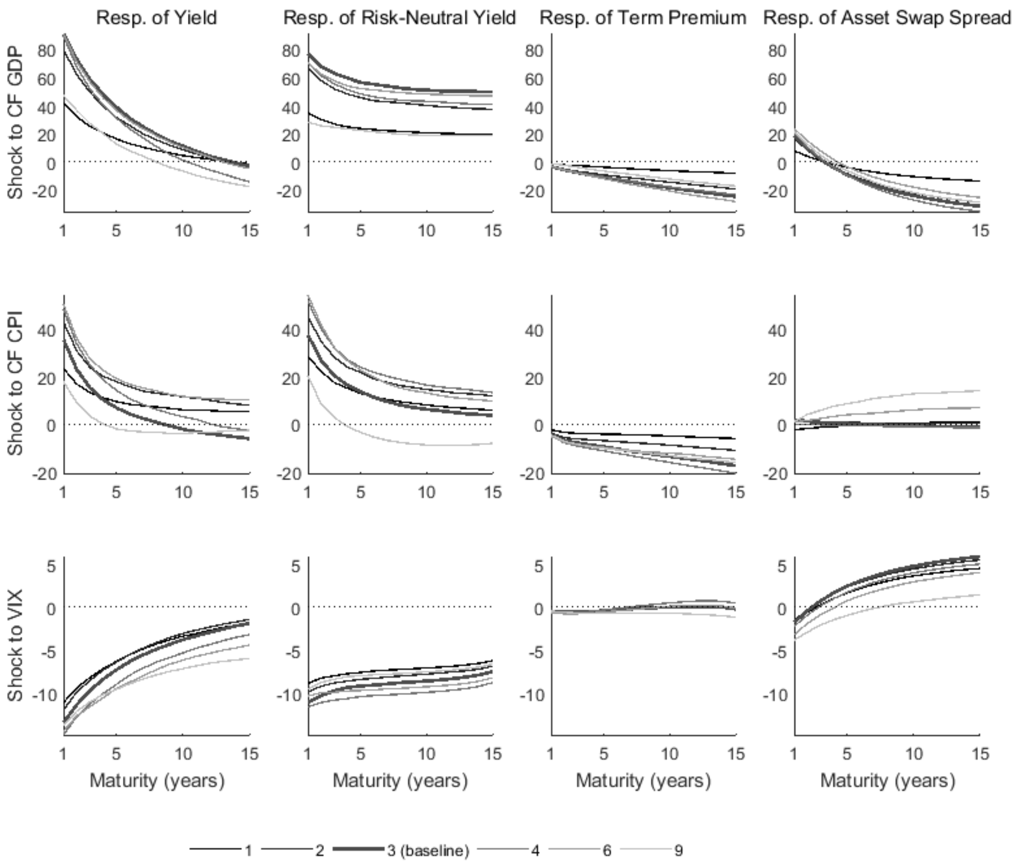


Figure C.5: Response for various shares of long-term forecasts (in bps)



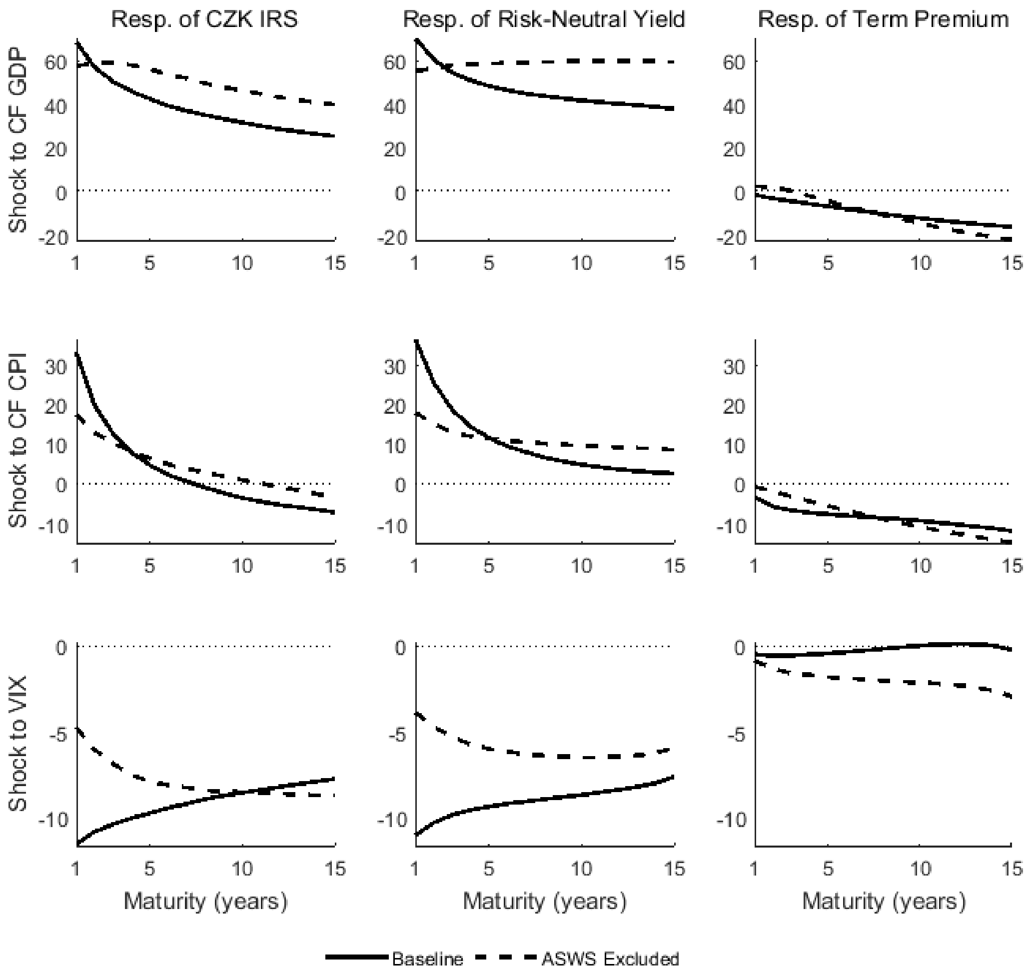
Note that the figure displays the response of the whole yield curve (1-15 years) to shocks after 12 months. See note to Figure 8 for a description of the plot elements. The shares 0-100% refer to the share of the long-term forecasts in the calculation of the CF GDP and CF CPI series.

Figure C.6: Response for various lags (in bps)



Note that the figure displays the response of the whole yield curve (1-15 years) to shocks after 12 months. See note to Figure 8 for the description of the plot elements.

Figure C.7: Response of CZK IRS after excluding ASWS (in bps)



Note that the figure displays the response of the whole CZK IRS curve (1-15 years) to shocks after 12 months. See note to Figure 8 for the description of the plot elements.

Appendix D

Response to Opponents' Reports

I would like to express my sincere gratitude to the opponents for reading and commenting on the thesis. I found the comments highly valuable; their incorporation improved the thesis significantly. This hols especially for the case of the comments to the Chapter 3, which were used to refine the paper before submitting it into a journal.

Below, I present the selected statements from the reports that required or recommend adjustments to the thesis. Below each statement, I provide my response and, in most cases, also describe the way it was incorporated into this final version of the thesis.

Chapter 3 (the second paper *Yield Curve Dynamics and Fiscal Policy Shocks*) was mostly commented on in the reports due to the fact that the paper was not published yet. Therefore, a significantly revised version of the paper was used to replace the original Chapter 3. The changes included partial revision of modeling framework, paper structure as well as certain references to the literature. The overall motivation, the contribution of the paper and the way how the results are commented on remained mostly the same. The revision can be summarized in the following way: The previous version of the paper used a narrative approach to show rather a surprising response of yields and then provided a set of robustness checks to further support the finding. The new version of the paper uses three equivalent "baseline" identification approaches, including both canonical approach as well as our narrative approach from the previous version of the paper. This allows us to better relate our results to the literature (Blanchard & Perotti 2002 in particular) and, simultaneously, present our results as an "extension" of the previous findings rather than their rejection.

The revision of Chapter 3 was used to incorporate the comments from the referee reports (see below). It must be noted, however, that further valuable comments from reports previously obtained together with a "reject" decision at the *American Economic Journal: Macroeconomics* were also reflected in the revised version. Therefore, the scale of revisions is wider than what the referee reports required.

In the case of Chapter 2 and Chapter 4, as these are built on already published papers, the comments were mostly incorporated either by adding footnotes or single paragraphs to the text or answered only in this Appendix.

D.1 Advisor's Report

General Comments

1 It would be good to check references and update unpublished or forthcoming items in the final version of the dissertation.

> I checked the references and updated them where needed.

2 Plus, some infrequent typos should be corrected.

> The thesis was checked once again and typos corrected where discovered.

3 Information on the publication outlets should be provided in the Chapter 1, as a final information related to each paper, and not in individual chapters.

> Adjusted, the information on the publication outlets were moved to Chapter 1 whereas the additional acknowledgments were included into the Acknowledgments section at the beginning of the thesis.

Chapter 2: Identification of Triggers of U.S. Yield Curve Movements

no specific comments or required adjustments

Chapter 3: Yield Curve Dynamics and Fiscal Policy Shocks

4 In terms of methodology, it might be good to use long and short rates in the SVAR model as an alternative to the term-structure model.

The revised version of the chapter includes three different ways of incorporating the yields into the models in order to support the robustness of the results. First, the short rate and a longer yield together entered the VAR models. Second, the level, the slope and the curvature were used to represent the yield curve instead. Third, the yield factors from an affine term structure model were used in the model to capture the dynamics of the whole yield curve. See Section 3.3 for details.

5 An updated version of the term-structure model from Bauer and Rudebusch (AER 2020) should be used to move the paper in line with the present literature.

Agreed, Bauer & Rudebusch (2020) is the affine model used in the revised paper, see Section 3.3.

6 In order to show robustness of results, several standard definitions of fiscal shocks should be used to assess what their effects are on the yield curve.

Implemented. The revised version of the chapter uses three different approaches to identify the government spending shocks: the SVAR-based identification in the spirit of Blanchard & Perotti (2002), the forward-looking to identify the government spending shocks several quarters before they are actually realized and enter the spending figures, and a shock identification within a DSGE model as a robustness check. See Section 3.2 for overall description and Sections 3.4–3.6 for description of results for each of the approaches.

7 For the robustness purpose, it would be also good to use model-free yield curve factors (level, slope, curvature) in order to account for the response of the entire yield curve.

Agreed, the revised version of the chapter uses model-free yield curve factors—the level, the slope and the curvature of the yield curve. See the response to the comment **4** above.

Chapter 4: The Czech Government Yield Curve Decomposition at the LB

no specific comments or required adjustments

D.2 Report by Prof. Roman Horváth, Ph.D.

General Comments

8 I would avoid the expression "confirms this hypothesis". We typically say that we reject or do not reject hypothesis but never confirm.

Agreed, thank you for noticing this mistake. Relevant sentences were rewritten so that such expression is not present in the text.

9 Small open economy should be used rather than "small opened economy".

Corrected.

10 The thesis should be formatted more in line with what we are used to in the other theses. For example, this text: "The paper was published in the North American Journal of Economics and Finance (2020, vol. 54, article 101288). The author thanks Evžen Kočenda, Aleš Maršál and two anonymous reviewers for helpful comments and suggestions. All remaining errors are my own." should not be placed below the section title but as the footnote.

Adjusted, although the information on publications and the acknowledgments were moved to Chapter 1 and to the Acknowledgment section at the beginning of the thesis, respectively, following the Comment **3** above.

11 The individual chapters should probably not have abstracts. There should be only one abstract for the whole thesis.

Abstracts were removed from the individual chapters.

12 Change Cholseki for Choleski.

Corrected.

Chapter 2: Identification of Triggers of U.S. Yield Curve Movements

13 The chapter 2 examines the effect of news of the yield curve at the daily frequency. How does the author treat the situations such as more than one news within the day? In addition, timing and sequencing of the news may play a role, too. Example: Suppose there are two news announced on Monday and Tuesday.

The Monday news from the vice governor says that the economic conditions are deteriorating. The Tuesday news from another vice governor says that she or he would like to confirm what the other vice governor said on Monday. Clearly, the Tuesday news should affect markets less (or do not affect at all). It also matters who provides the news (for example, governor vs. bank board member). The central bank communication literature, which examines the effect of news on financial markets, has evolved substantially into analyzing the rich structure and various peculiarities of the news and it would be interesting to extend the chapter in this direction. Another interesting extension would be to examine that no news are in fact news. Suppose that the frequency of central bank communication decreases and central bankers start informing the markets less frequently than before.

In the case more than one headlines appear within single day, either in one or more shock categories, the model treats each of these headlines as a single innovation. The change in yields for that particular day is explained in terms of the sum of the magnitudes of the individual innovations premultiplied by the time-varying parameters, see (2.4).

I agree with the comment on the possible further detailed analysis of the central bank communication or an absence of central bank announcements. I would like to highlight, however, that such analysis would require more detailed analysis of the headlines in a narrative sense. This would be extremely time-consuming for the number of the headlines I use (more than three thousand) — I used automated algorithms searching for keywords to identify and categorize the headlines, rather than narrative evaluation of each single headline. Furthermore, only less than 15% of the headlines in my analysis represent central bank communications (see Table 2.1). Therefore, the analysis proposed in the comment would require a different set of shocks as well as a different modelling technique (given much less shocks available). I therefore leave such analysis for consideration for a future research.

14 Chapter 2 talks about non-macroeconomic factors associated with the capital flight and mentions the eurozone debt crisis as the example of non-macroeconomic factor. This is not clear. Debt crisis are typically related to macroeconomic issues. The thesis should explain more accurately what is meant by the non-macroeconomic factors.

Thank you for highlighting this inaccuracy. The non-macroeconomic factors are considered from the perspective of local macroeconomic conditions in the U.S. To fix this, the term non-macroeconomic was replaced several times by the phrase "factors beyond U.S. macroeconomic conditions" or similar in Chapter 1 and Section 2.1 to explain the aim of the paper better. Also, at the beginning of Section 2.2, a footnote was added to explain the use of the term "non-macroeconomic" in the non-U.S. macro perspective for the rest of Chapter 2.

15 More generally, the Chapter 2 argues (and provides compelling evidence) that traditional macroeconomic factors play a smaller role for yield curve than they used to play. The thesis argues that some other factors such as non-macroeconomic news related to capital flight gained prominence. However, the thesis should focus more on an explanation why macroeconomic factors become less important. Is it because of heighted economic policy uncertainty? Political polarization or political instability? Or is the globalization a cause why domestic macroeconomic factors lose their importance?

I, generally, agree, that the causes should be outlined somehow. To incorporate this comment, I added a discussion on the possible explanations of causes of the captured trend into Conclusion of Chapter 2, the second paragraph. An empirical evaluation of the causes themselves would be, however, way beyond the scope of the paper. It would require use of different data (see also the response to the Comment **13**), including measures of shifts in monetary policy, international capital flights etc. Furthermore, such analysis be complicated by the fact that the trend in not particularly long - see Figure 2.5. The related literature, in case it notices the trend, mostly discusses it without providing further econometric evaluation (see, for instance, Bauer 2017).

The aim of Chapter 2 is to find news-based evidence that the trend exists, which I believe is a sufficient contribution. But overall, thank you for this comment which provides attractive idea for a future research.

Chapter 3: Yield Curve Dynamics and Fiscal Policy Shocks

16 Chapter 3 examines the effect of various types of fiscal shocks on the yield curve. It is unclear after reading the abstract and introduction, how the authors analyze this question. Is it a vector autoregression model, dynamic general equilibrium model or a different type of model? I would spend a sentence or two to inform the reader more up front.

I agree. The new version of the paper explain the empirical approach explicitly in the second paragraph of Section 3.1—we newly utilize multiple VAR models with various fiscal policy specification and yield representation.

17 Chapter 3 also states that it uses the Laubach and Williams (2003) estimates of the neutral rate (rstar). Borio and Cukierman has criticized this approach on various grounds, arguing that the Laubach and Williams approach results in downward biased estimates. For example, Cukierman (see here: https://voxeu.org/article/natural-rate-interest-its-measurement-monetarypolicy-and-zero-lower-bound) argues that we need the long-term risky neutral rates rather than those that take the approach of Laubach and Williams (2003) and their followers. For this reason, Juselius, Borio, Disyatat and Drehman (2017) in their International Journal of Central Banking article (see here: https://www.ijcb.org/journal/ijcb17q3a2.pdf) provide an alternative modelling framework, which estimates the neutral rate accounting for financial cycle. This thesis is about modelling macro-finance interactions more in a spirit of Juselius et al. (2017) rather than macro-no finance interactions as is the case for Laubach and Williams (2003). Therefore, I find the choice of Laubach and Williams (2003) estimates to be a bit in contradiction to the main message of thesis. A small remark: the authors of this chapter apparently use some updated estimates of Laubach and Williams (2003) given that their sample period ends in 2019, this should be noted somewhere in the footnote.

This is a good point. I solved it in the new version of the paper in the way that the external rstar estimate is not used at all—following Bauer & Rudebusch (2020), we consider the rstar (τ_t variable in our notation) as unobserved and estimate it within the Bayesian framework.

18 The Chapter 3 also states that: *We also consider a variable representing the general uncertainty perceived by the financial markets* but later notes that it uses the economic policy uncertainty by Baker et al. (2016). I am sure that the economic policy uncertainty and the financial markets uncertainty measures will be positively correlated but this correlation will not be unitary, i.e., the measures will share common trend, but the peaks of the uncertainty series will differ. The measures of uncertainty in the financial markets are available and should be considered. For example, Sydney Ludvigson provides (and updates) financial uncertainty index on her website: https://www.sydneyludvigson.com/macro-and-financial-uncertainty-indexes. The indexes are based on her research with the co-authors published in the American Economic Review and in the American Economic Review: Macroeconomics.

I agree with the point and thank you for the reference. In the new version of the paper, we kept only the fiscal policy uncertainty index by Baker *et al.* (2016), not the general policy uncertainty. This simplified the models (note that explaining the impacts of the general policy uncertainty was not the core aim the paper), made the results more robust. Simultaneously, as I believe, the omission of the general policy (or financial market) uncertainty did not weaken the model properties, given that the Treasury yields reflect the information on the financial market uncertainty as well (in fact, the flight to/from quality and the behavior of bond risk premia were largely commented on in the discussions on the model outputs).

19 Chapter 3 also presents the impulse responses. However, the responses are typically not statistically significant. Does it suggest that the fiscal policy-yields interactions are weak and statistically insignificant? Or it is a consequence of over-parametrized vector autoregression model? After all, the authors use a seven variable vector autoregression model with five lags. They show the corresponding figure with the information criteria (AIC and BIC) in the Appendix. BIC recommends only 2 lags. Maybe the authors should consult the research by Ivanov and Kilian (2007) (published in the Studies in Nonlinear Dynamics & Econometrics 9(1):1219-1219), who provide some guidelines on how to select the optimal lag length. The BIC criterion typically outperforms in small samples.

I agree that the previous version of the Chapter 3 used perhaps rather over-parametrized VAR model. In the new version of the model, more parsimonious models are used instead. Luckily, the responses are much more significant now. Note that we still use 68% confidence intervals, which is not uncommon in the literature dealing with fiscal policy (at least at Ramey (2011) and several others). However, most of the new results would remain significant for even 90% intervals.

Thank you a lot for the reference on the optimal lag selection literature. I newly used HQC a SC instead of BIC, given the hints from the mentioned paper, and also referenced this paper in the text.

Chapter 4: The Czech Government Yield Curve Decomposition at the LB

20 Chapter 4 examines the driving forces of the Czech government bond yields. It is a nice policy-oriented contribution and extensively analyzes the specificities of the Czech market. It argues that negative yields that prevailed on the market for some time period cannot be fully explained by the expectations. The chapter shows how portfolio effects related to the lifting of the exchange rate floor policy matter. While chapter 3 uses vector autoregression model, chapter 4 uses the Bayesian approach to vector autoregression. Why do we need Bayesian approach in this chapter?

Given the shorter historical time-series for Czech government bond yields, as compared to the U.S. yields history, the use of Bayesian approach in this case helps to ensure that the model avoids over-parametrization thanks to the use of priors.

21 The black and white figures in Chapter 4 are difficult to read (grey colors are too similar to each other).

Agreed, pictures were adjusted to include colors instead of shades of grey.

D.3 Report by Prof. Ing. Martin Mandel, CSc.

General Comments

22 The contents of the articles correspond to the title of the dissertation. However, it would be possible to formulate the title of the dissertation more specifically, ie with an emphasis on the term "yield curve" in the title of the dissertation.

Agreed, thank you for the idea, the title was changed to more specific "Topics in Yield Curve Modeling".

23 In accordance with the requirements, dissertation thesis includes a "General introduction", which has only about 6 pages. I believe, that this introductory section could contain a deeper historical anchor of the analyzed problems. The analysis of the yield curve and the definition of the term premium have their historical roots in the key works of J. M. Keynes (A Treatise of Money and The General Theory of Employment, Interest and Money), in which he discusses the problem of uncertainty and risk in connection with the risk and liquidity premium. An indicative overview of this matter is provided, for example, by the article by Fantacci, L., Marcuzzo, MC, Sanfilippo, E. (2014): A note on the notions of risk-premium and liquidity-premium in Hicks's and Keynes's analyzes of the term structure of interest rates, European Journal of the History of Economic Thought,(21) 6.

I agree and thank you for proposing the extension of the introduction. I used the mentioned works to provide deeper description of the historical literature focused on the interest rates and risk premia in general. Several paragraphs were added or adjusted in Chapter 1, pages 2–3.

24 The author of the dissertation presents Graph 1.1 in the General Introduction, in which he documents the relationship between the interest rate spread (ie the slope of the US yield curve) and the economic cycle. In this connection, I believe that the author should have primarily cited A. Estrella's analytical works (eg Estrella, Arturo, and Gikas A. Hardouvelis (1991): The Term Structure as a Predictor of Real Economic Activity. The Journal of Finance, (46)2). The author of the dissertation considers the interest rate spread as the difference between 10 years and 2 years of US Treasury yields. A. Estrella and T. Adrian (Monetary Tightening Cycles and the Predictability of Economic Activity, Economics Letters, 99 (2) consider the interest rate spread as a combination of 10 years and 3 months to be more suitable.

Question No.1: What specific interest rate spread do you consider to be the best leading indicator for predicting a recession?

Thank you for mentioning the work of A. Estrella, the reference was added into Chapter 1, together with a footnote elaborating shortly on the various spreads.

Answer to the Question No.1: Following the recent work of Bauer & Mertens (2018), I tend to view the differences between the predictive powers relatively small, especially when considering the spread as an early warning indicator for the future recession. Still, intuitively and without substantial evidence, I would argue that the 10Y-3M spread is more sensitive to the changes in the Fed fund rate and therefore generate more crisis "warning signals" even in case the yield curve inverts for only short period. The 2Y yield should be slightly less volatile, reflecting the material changes in the expectation about monetary policy over next two years rather than even smaller temporary changes, therefore would produce the "warnings" less frequently and the warnings would signal more severe crises rather than just recessions.

Chapter 2: Identification of Triggers of U.S. Yield Curve Movements

no specific comments or required adjustments

Chapter 3: Yield Curve Dynamics and Fiscal Policy Shocks

no specific comments or required adjustments

Chapter 4: The Czech Government Yield Curve Decomposition at the LB

25 In the theoretical definition of the term premium, Shiller (1979) and his "narrow definition as a compensation for uncertainty" are cited in dissertation. On page 61, the author of the dissertation decomposes the risk premium into "pure term premium, credit risk premium and portfolio effect". On page 63, he states: "The term premium applies to the maturity of the bond and is a compensation for interest rate rate risk." The explanation of the term premium, which is historically associated with liquidity premium theory, is a relatively complicated theoretical and empirical problem. I am of the opinion that it is necessary to respect the liquidity approach, ie Keynes's psychological explanation associated with uncertainty or financial interpretation through transaction costs (ie wider bid-ask spread between long-term assets and short-term assets). These approaches clearly penalize investment in long-term assets. The term premium in the concept of risk premium (reward for higher market risk) can, in my opinion, paradoxically, penalize gradual investment in short-term bonds, because we work with expected yield rates in the calculation. In my opinion, there is no clear answer to the question of the effect of market interest rate risk on the yield curve, as from the market entity's point of view it depends a) on its strategy to hold or not hold long-term bonds to maturity and b) on the relationship between the time structure of assets and liabilities (segmentation theory and preferred habitat theory).

Question No. 2: Based on what specific balance sheet positions and speculation strategies do you define your term premium concept (page 63)? Can this term premium have both positive and negative values?

Thank for this comment that, from my point of view, supports my observation on the dichotomy in the view on the yield curve from the point of view of the macroeconomics and the financial economics. As the question motivated me to further improve my understanding on the dichotomy, I dare to offer a rather extensive response below.

I believe that the Keynes's explanation and the "compensation for interest rate risk" explanation of the risk/term premia are not mutually exclusive. As I understand from Fantacci *et al.* (2014), page 4, Keynes did not believe that the risk premia can be calculated explicitly, and his view on the term premia was more theoretical. The financial economics, on the contrary, builds more on the work of Hicks and his view on risk premia as the compensation. The financial economics and especially the no-arbitrage asset pricing uses multiple assumptions to be able to obtain a representation of the market price of risk (as well as the term premia themselves) that can be calculated. The thesis builds on the affine no-arbitrage term structure models that are part of the financial economics, i.e., I implicitly use such assumptions to be able to calculate the risk premia - which I need to demonstrate the nature of the factors affecting the yields and the propagation mechanism.

The assumptions used by the no-arbitrage pricing include, for example, the absence of transaction costs or the assumption that the return-risk relation is the only interest of the investors. This means that some of the explanations of the term premia in the comment (transaction costs, preferred habitat theory) are directly excluded by these assumptions – this explains why the concept of the term premia used in this thesis and in the no-arbitrage yield curve modeling in general is narrower than the theoretical Keynesian view.

To explain more the details on the definition of the term premia, I have added discussion about this dichotomous view on the risk premia into the introduction, page 3. I have also added a reference to this discussion into Chapter 4 (footnote No.2) so that the mentioned definition of the term premia is linked to the broader context.

Answer to the Question No.2: Given the stated above and the new discussion in the introduction, the no-arbitrage pricing assumes that the investors earn the short rate as the risk-free yield on funds. Given this assumption, my premium concept can be defined from the point of view of either an investor that borrows for the short risk-free rate or an investor that has certain amount of funds and compares a possible investment opportunity with the case that they would invest in a risk-free investment (a current bank account). In both cases, the gradual investment in the short-term bonds represents the risk-free alternative by the assumption of the no-arbitrage, an any additional excess yield needs to be explained by the risk premia. Such view is not my personal view but rather a basic concept of the whole no-arbitrage pricing literature that I follow in my research.

The fact that some of the assumptions of the no-arbitrage pricing are not fulfilled, i.e., there is some specific source of demand for the bonds beyond the risk-return relation, is considered in Chapter 4 by the presence of the "portfolio effect" component in yields. In fact, the paper was motivated by the fact that the Czech government bond market clearly diverged from the no-arbitrage market in the period before the exit from the exchange rate floor regime - the canonical affine no-arbitrage models were not providing unbiased results under such conditions and the paper tried to propose an approach that still made the Czech yield curve modeling possible.

26 The use of the yield curve for predictive activity is based on the assumption of rational market entities that realize forward-looking expectations. If we evaluate the annual forecasts of financial analysts in the area of PRIBOR 1 Y and SY IRS (CZK) for the period 2007-2020 (Source: CNB, Financial Market Inflation Expectations), we find that their predictions practically copy the actual observed values at the time of making the forecast. Analysts usually explain the high adaptability of their predictions by the fact that a large number of predictions is made by a small team.

Question No. 3: Is it possible to observe a different way of shaping and behavior of the yield curve for US government bonds and Czech government bonds?

Answer to the Question No.3: The differences are difinitely present, given the specificities of both the U.S. and the Czech government bond market. In the case of the U.S., the Treasuries serve as a safe haven for large portfolio managers both from the U.S. and globally. Therefore, using the example of a rotation of the yield curve before a crisis, any information that motivates the Fed to increase rate to slow-down overheated economy may also cause the institutional investors to expect future slowdown (either due to the Fed hike itself or any signal of the overheated economy that implies certain risks). The investors might start rotating their portfolios from equities to Treasuries or from emerging countries to the U.S., both increasing the demand for Treasuries and therefore reducing the longer yields despite the Fed hike at the short end - which causes the rotation. On the contrary, the Czech government bonds do not represent such safe haven for foreign investor, who may perceive the Czech republic as an emerging country and therefore tend to decrease their local investments (resulting in an increase in yields) already several quarters before a recession (especially taking into account that the small open economy as is the Czech Republic usually imports a recession from abroad with certain lag, i.e., in the time when the international investors are already gone.)

Furthermore, there were certain events specific for the Czech government bonds that were not present in the U.S. Namely, (1) the eurozone debt crisis led to a spike in longer-term yields unrelated to local macroeconomic conditions, and (2) the Koruna exchange rate floor motivated unprecedented inflow of foreign investments during 2016–17 resulting in record-low both short and long Czech government bond yields (see figure 4.2). Both these events resulted in specific shapes of the yield curve that were unrelated to the domestic business cycle and interpretation of the yield curve shapes without knowing the national specificities could be misleading.

D.4 Report by Prof Martin Berka Ph.D., M.A., ABFER

Chapter 2: Identification of Triggers of U.S. Yield Curve Movements

no specific comments or required adjustments

Chapter 3: Yield Curve Dynamics and Fiscal Policy Shocks

27 The Chapter is finely executed, but could benefit from a better placement into, and a discussion of, broader macroeconomic literature on fiscal policy. A core prediction of many macroeconomic models (especially neo-classical models), and a key policy discussion point in this respect, is the crowing-out effects of the monetary policy. The crowding-out hypothesis links the fiscal expansion to a higher demand for borrowed funds and predicts an increase in short- and long-term interest rates. Translated to yield curve, the crowding-out hypothesis would predict that the yield curve shifts up following a fiscal expansion (the shape of the shift may depend on the maturity of the government borrowing, as well as the delay between the announcement and the actual expenditure). Instead, in Chapter 3, we see an estimated shift down of the yield curve following an increase in government spending (although this is only significant for the anticipated effects, and only at a 1-year horizon). I think the authors would benefit from more detailed discussion of the links to the empirical literature on crowding-out effects of public finance.

> This is a great point and I fully agree that the original version of the Chapter 3 neglected it. The new version of the paper explicitly names possible transmission channels of the fiscal policy shock into the yields (see response to the next comment) and also links one of the channels to the crowding-out effect hypothesis in Section 3.2. It is now also emphasized that the timing of shock and its propagation is crucial when interpreting the identified initial downward shift in yields: the findings provide a wider picture rather than contradicting the consensus from the literature. Whole new section on the detailed discussion on the results and the links to the literature (mentioning the crowding-out effect but also other effects that are related to the fiscal policy-yield curve nexus) was added as Section 3.7.

28 A more general comment on this chapter is that it could benefit from a more detailed discussion of the possible channels of interaction between fiscal policy and financial markets. While a theoretical model would be welcome, it's certainly not necessary. I know you discuss some of your results in the light of the literature in section 3.9, but it is brief, and you may want to invest more effort here because it helps identify your contribution. There are many theoretical models out there to borrow from, and even a simple discussion of these, with a list of possible channels for possible influence of a fiscal expansion on interest rates (yield curve) would help reader understand the contribution of your paper better. You could consequently discuss the light your empirical results shed on the various theoretical approaches in macroeconomics.

I extended Section 3.2 to name and describe the possible channels explicitly, referencing to the relevant literature. To further support the fact that the channel have basis in the economic theory, I used the IS-LM model as an example to describe how some of these channels would be translated into the theoretical concepts—see one of the footnotes added to Section 3.2. On the other hand, I prefer to avoid further discussions of the theoretical explanations of the transmissions, given that the paper is intended to fill a gap in a yield curve literature rather than a fiscal policy and general macroeconomic literature: the yield curve literature is mostly highly empirical and only rarely provides theoretical concepts, which I aim to follow.

29 While the authors are aware of the much-cited contribution by Ramey (2011), I wonder whether it would be feasible or worthwhile to provide an additional set of results where fiscal expenditures are more tightly identified by focusing on the defense spending (in line with Ramey (2011)). It is true that will require additional work but it would make the contribution clearer, and obviously address an obvious comment a referee in high-ranking journal will make.

Thank you for the idea. In fact, this was our initial aim, we tried to use Ramey (2011) shocks directly. However, we discovered the number of the defense spending shocks is relatively low when focusing on the period starting in mid-80s, i.e., much later than Ramey (2011). Therefore, these shocks were not be able to explain a sufficient share of volatility in Treasury yields and the results were in general weak and not robust. Note also that the volatility of consumption, as focused on by Ramey (2011), and of yields differs significantly, and that the yield curve represents multi-dimensional structure that needs more variables to enter the VAR model and therefore requires more information to avoid over-parameterization.

To incorporate this comment, I better explained in the new version of the paper why it is reasonable not to move the beginning of the sample period further into the past and, explicitly, that the number of defense spending shocks would be too small in our case. See Section 3.5, the second paragraph, for details.

30 Another interesting result that may warrant closer discussion for a publication are the effects of uncertainty. Here, there is a booming literature started in part by Nick Bloom and co-authors, and I think you could find more links to that literature (though I note you cite one of his papers). This is particularly relevant because shocks to uncertainty do move the yield curve more meaningfully than fiscal policy shocks, in your study. Again, a discussion of possible channels, with a link to a few possible theories, would make this contribution clearer.

The new version of the paper uses more parsimonious VAR models, which give only a limited weight on the uncertainty indices—the fiscal policy uncertainty index is used only in case of single model specification as a robustness check, whereas the general uncertainty shock is not present in the new version at all (see also the response to comment **18**). The present results show that the effect of the fiscal policy uncertainty shock matches rather than exceeds the effect of the government spending shock.

Still, I agree with the comment and provide slightly extended discussion of the effects of uncertainty and the related literature in a newly added Section 3.7 (the last paragraph).

31 I'd also welcome clearer discussion at the end of your robustness checks on the link between the Zero Lower Bound results and the literature on ZLB. For obvious reasons (just think basic IS-LM model), fiscal policy is expected to be much more potent in the situation when interest rates are near zero. But in your Figure 3.11, what we see is that the results are actually more muted in the data. I know your estimation is atheoretical, but it would be worth either calculating the confidence intervals or in any case discussing the seemingly counter-intuitive results.

In the new version of the chapter, this robustness check is missing—therefore there is no need to provide the discussion.

However, I would like to provide some intuitive explanation of the results in the original version of the chapter. I agree that the fiscal policy is potent when interest rates are near zero. The fiscal policy may affect economic conditions effectively, but the yields may not respond to it at the ZLB. The reason for the limited response of yields is that the expected future volatility of the short rate may be limited under ZLB and the yield curve overall flat. Using the concept of the shadow rate, when the shadow rate is well below zero, the markets “perceive” that the Fed funds rate will not move for some time, and hence will not price the economic shocks into the yields in a full extent—they will wait first until the shadow rate “hits” zero from below and only then start pricing the future increases in the short rate in a full extent. Naturally, such explanation does not account for possible unconventional monetary policies (quantitative easing, for example), but it offers an intuition why the shadow-rate models imply generally sluggish response of longer yields at the ZLB.

Chapter 4: The Czech Government Yield Curve Decomposition at the LB

no specific comments or required adjustments