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TREASURY SUPPLY SHOCKS AND THE TERM STRUCTURE OF INTEREST RATES IN THE UK

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Treasury Supply Shocks and the Term Structure of Interest Rates in the UK*

(Államkötvény kínálati sokkok és a kamatlábak lejárati szerkezete az Egyesült Királyságban)

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Abstract

How does the additional debt issued by the government affect the term structure of interest rates? In this paper we identify Treasury supply shocks using intraday high-frequency data, by exploiting the institutional setup of the UK government bond primary market. We find that supply shocks have positive effects on nominal and real interest rates. Most of the reaction is due to real term and inflation risk premia rather than the expectation component of yields. We argue both theoretically and empirically that supply shocks transmit via the repricing of duration and inflation risks in the economy. We also document that these effects are stronger under adverse economic and financial conditions.

JEL: JEL: E43, E44, E60.

Keywords: Term structure, Government debt, Bond risk premia, High-frequency identification.

Összefoglaló

Hogyan hat az állam által kibocsátott addicionális adósság a kamatlábak lejárati szerkezetére? Ebben a tanulmányban államkötvény kínálati sokkokat identifikálunk magas frekvenciájú adatokkal, kihasználva az Egyesült Királyság Államadósság Kezelő Központjának az adósság kibocsátási mechanizmusát. Eredményeink azt mutatják, hogy a sokk pozitívan hat mind a nominális- mind a reálkamatokra. A reakció túlnyomó részben a reál lejárati prémiumnak és az inflációs kockázati prémiumnak, kisebb részben pedig a magasabb rövid oldali kamatvárakozásoknak tulajdonítható. Mind empirikusan, mind egy elméleti model keretei közt is úgy érvelünk, hogy az államkötvény kínálati sokk a lejárati és az inflációs kockázatok átárazása által fejti ki hatását a hozamgörbére. Eredményeink azt mutatják, hogy ez a hatásmechanizmus erősebb piaci turbulencia és negatív gazdasági kilátások idején.

1 Introduction

How does the additional issuance of government debt affect the term structure of interest rates? The question is both important and topical given the rapid increases in government deficits and debt levels across the globe due to the Covid-19 pandemic. At the same time, the interest rate environment is currently on the rise, due to central banks efforts to fight the inflationary pressure of the recovery. The resulting increased public debt service cost requires the active management of the debt and a good understanding of the financial market effects of debt issuance.

The effect of government debt issuance on interest rates is not well established in the empirical literature. Surveys on the effects of fiscal deficits on interest rates by Gale and Orszag (2003) and Engen and Hubbard (2004) found around the same number of papers with positive and significant effects as the number of papers with insignificant effects. The reason is that identification is difficult. Reverse causality, common factors and anticipation effects are all responsible. While interest rates are available at every point in time, budgetary variables are only available annually or at best quarterly frequency. Agents often anticipate and price public policies, such as new debt issuance, in advance, making it difficult to measure the true causal effect. Factors affecting both variables can lead to finding spurious relationships: while central banks cut interest rates in a recession, fiscal deficits and debt issuance tend to increase (Laubach (2009)). Therefore, our goal in this paper is to shed light on the causal effect of new debt issuance on interest rates.

Understanding the impact of changes in Treasury supply is relevant for policy makers for two main reasons. Given the ever-increasing financing needs of governments, fiscal authorities need a thorough understanding of how their funding decisions affect financial markets. This has direct impact on their own funding costs, as well as on the overall interest rate environment firms and households face. Second, central banks are currently in the process of winding down their accumulated large asset portfolios through quantitative tightening (QT) programs. To the extent that this is done via outright Treasury sales, our results can provide estimates of the potential effects of quantitative tightening on financial markets.

Our first contribution is to propose a novel identification of government bond supply shocks. While the fiscal policy literature uses quarterly or annual deficit statistics to uncover the effects of debt issuance, we focus on days with government bond issuance announcements. Moving to higher frequency has the advantage of allowing for an (arguably) cleaner identification, at the expense of being more restricted in the range of addressable research questions.

Our identification exploits the institutional features and operations of the Debt Management Office (DMO) of the United Kingdom. We focus on intraday bond futures price movements in a narrow event window around the *announcements* of bond auctions. The UK DMO does not provide information about the volume of the upcoming auctions before these releases, so the information content of the announcements is high. Furthermore, the announcements contain information solely on the supply side of the bond market. This institutional framework provides an ideal setting to apply the high-frequency identification scheme. Price movements in a narrow event window around the announcements can be related to information about future bond supply. We interpret these price movements as shocks to the supply of government bonds.

The second contribution of the paper is to study the effects of supply shocks on the term structure of interest rates. We find significant positive effects on nominal interest rates: a positive standard deviation supply shock increases nominal rates by 1-1.5 basis points. As longer maturities respond more, the slope of the yield curve increases. This effect spills over to equity and corporate bond markets. To give more intuition on the size of the effect, we provide a back-of-the-envelope exercise. On the 11th of March 2020, the UK government announced a Covid-19 support package of £12bn. According to our estimates, an unexpected debt issuance announcement of this size would raise nominal yields by 13-19 basis points. These estimates are in line with actual changes in benchmark yields that day.

Next, we study how supply shocks transmit to the term structure of interest rates. A standard deviation supply shock increases real rates by 1-1.2 basis points, implying that higher inflationary concerns are not the main driver of the effect on nominal rates. Therefore, to shed more light on the transmission, we decompose yields into expectations and risk premia components with

the Affine Term Structure Model (ATSM) of Abrahams, Adrian, Crump, Moench and Yu (2016). We find that over two-thirds of the response of long-term yields are attributed to the risk premia components. Additional supply of government debt raises both the real term premium and the inflation risk premium. This implies that the supply shock mostly operates via the "risk taking channel" i.e., investors repricing risks in the economy.

We illustrate this finding in an equilibrium term structure model of nominal and inflation-linked bonds with supply effects. The model builds on Greenwood and Vayanos (2014), extending their model with inflation risk. The supply of nominal bonds is stochastic, and shocks to the supply are absorbed by risk averse investors, holding more inflation and interest rate risks in their equilibrium portfolio. As investors become more exposed to these risk factors, they require higher compensation, driving up risk premia, and consequently, yields. As inflation-linked bonds are unaffected by inflation risk, their yield is less affected by the shock compared to nominal bond yields, consistent with the empirical findings.

The mechanism in the model is closely linked to investors' limited risk bearing capacity. Supply effects are stronger when investors are more risk averse. We test this prediction empirically, by exploring state dependence in the effects of the high-frequency supply shock. Consistent with the models' prediction, we find stronger reactions of yields in times of market stress, driven by rising risk premia. We also explore non-linearities in times of high unemployment and at the effective lower bound of the policy rate, as the fiscal policy literature found state dependence in such environments (Auerbach and Gorodnichenko (2012), Christiano, Eichenbaum and Rebelo (2011)). We find that long-term yields react stronger to the supply shock during these periods. The main driver here is again rising risk premia and not higher expected short rates. Our findings are consistent with papers documenting larger asset price reactions to Treasury demand shocks (Lengyel and Giuliodori (2022)) and monetary policy shocks (Basistha and Kurov (2008)) in similar environments.

The rest of the paper is organised as follows. Section 2 connects our paper to the literature. Section 3 explains our identification in two steps. Section 3.1 describes the institutional framework of the UK government bond primary market, while Section 3.2 explains how we exploit this to construct the supply shock. Section 4 analyses the effect of the supply shock on yields. Section 4.2 demonstrates that the supply shock transmits by affecting risk prices. Section 4.3 presents an equilibrium asset pricing model where we illustrate this effect. Section 5 investigates the role of non-linearities. Lastly, Section 6 concludes.

2 Related literature

We identify government bond supply shocks using the high-frequency identification (HFI) method. This was developed initially to study the effects of monetary policy shocks (Kuttner (2001), Gürkaynak, Sack and Swanson (2005)), and it has recently been applied to identify oil price shocks (Känzig (Forthcoming)), carbon policy shocks (Känzig (2021)) and Treasury demand shocks (Droste, Gorodnichenko and Ray (2021), Lengyel and Giuliodori (2022)). The latter is the application most similar to ours. Droste et al. (2021) identifies Treasury *demand* shocks of large institutional investors by following Treasury futures prices around Treasury auction result releases. We focus, on the other hand, on the *announcements* of auctions. In this aspect, the paper by Simon (1991) is closely related to ours. Simon (1991) analyzes the announcements of US government cash-management bills in an event study. The focus of both Droste et al. (2021) and Simon (1991) is on the segmentation of Treasury markets and on the localized effects of supply and demand conditions. While we do find some evidence for segmentation, our main focus is on risk pricing and the transmission of government debt supply shocks.

During the finalization of our results, we became aware of Phillot (2021). Similar to us, he proposes the identification of US Treasury supply shocks by following futures price movements around auction supply announcements. In line with our results, he finds that the supply shock is followed by a positive shift in the yield curve, higher inflation compensation, rising stock prices and corporate bond yields. The main differences compared to our paper are the following. Firstly, we follow *intraday* futures price movements in a one-hour event window around announcements, while Phillot (2021) records the price difference between the closing price on the announcement day and the closing price on the previous day. The narrower event window means that our shock series is potentially less affected by confounding factors that can contaminate the results. What allows us to go higher in frequency is focusing on the United Kingdom instead of the US. In the UK the exact publication time within the day is known, while in the US it is not. This allows to zoom in on high-frequency price movements around the announcements. An additional benefit of the UK primary market is that (as Section 3.1 explains) UK auction announcements have higher information content on the supply side of the market compared to the US, due to the institutional setup of the UK DMOs' operational framework. The second difference between our studies is our more focused attention on the term structure of interest rates and bond risk premia. We illustrate both empirically and theoretically that the transmission of the supply shock is through the repricing of interest rate and inflation risks in the economy. Phillot (2021) on the other hand focuses more on the persistence of the effects of the supply shock.

Supply and demand conditions in Treasury markets have gained much attention with central banks' QE operations. The general finding is that official demand for bonds decreased the level and slope of the yield curve (Hamilton and Wu (2012), Li and Wei (2013), Kaminska, Liu, Relleen and Vangelista (2018) and others). The underlying mechanism is explained by the preferred habitat theory of the term structure (Modigliani and Sutch (1966), Vayanos and Vila (2021)). This theory argues that changes in the demand and supply conditions are transmitted through bond risk premia. Risk premia has a positive relation with the slope of the term structure, as long-term bonds are more exposed to risks. Our study brings evidence in line with this literature, connecting bond supply with the level and slope of the yield curve, as well as with the bond risk premium. However, in contrast with the empirical literature on QE, we do not focus on changes in central bank demand for bonds, but on the supply from the Treasury. Nevertheless, the mechanism we explain our findings is the mirror image of the one used to explain the effects of QE (Vayanos and Vila (2021), Greenwood and Vayanos (2014)). Our results are more useful to analyse the effects of debt financed fiscal expansions or the effects of quantitative tightening (QT) programs.

The transmission mechanism is that as bond supply changes, investors reprice risks in the economy due to the change in the quantity of risk they hold in their portfolio. Spending and financing decisions of the government, therefore, changes the amount and the price of risks. In this regard, our paper is connected to the relatively new strand of literature that establishes a connection between measures of fiscal policy and risk pricing. Studies found that bond risk premia is affected by the level of fiscal expenditures and the uncertainty around it (Bretscher, Hsu and Tamoni (2020), Horváth, Kaszab and Maršál (2021), Kučera, Kočenda and Maršál (2019), Bayer, Born and Luetticke (2020)), the government debt ratio (Alesina, De Broeck, Prati and Tabellini (1992), Greenwood and Vayanos (2014), Nguyen (2018)) and the maturity structure of the debt (Chadha, Turner and Zampolli (2013), Greenwood and Vayanos (2014), Corhay, Kind, Kung and Morales (2021)). The government debt ratio was also found

to influence equity- and credit-risk premia (Gomes, Michaelides and Polkovnichenko (2013), Liu (2019)) as well as the liquidity premium (Krishnamurthy and Vissing-Jorgensen (2012), Bayer et al. (2020), Reis (2021)).

3 Constructing the supply shock measure

3.1 DESCRIPTION OF THE UK PRIMARY BOND MARKET

The UK Debt Management Office (DMO) is the institution responsible for the UK Governments' debt management policy. It carries out this duty by issuing debt securities denominated in pound sterling. In this section we describe the institutional details of the bond issuing process. For more details see DMO (2021).

The securities with maturity within a year are called bills, while the securities with maturity over a year are called "gilts" or "gilt-edged securities". Gilts make up the largest proportion of government debt, around 86% (see Figure 1). The DMO issues two types of gilts: Conventional and index linked. Conventional gilts are nominal bonds i.e., interest payments and coupon repayments are fixed in nominal terms. They constituted almost three quarters of the gilts issued by the DMO in recent years. Index-linked gilts are securities with coupon and final redemption payments linked to inflation, more specifically to the UK Retail Price Index (RPI). They constitute around a quarter of the debt issued by the DMO. The primary means of issuing gilts is through regular auctions, with over 75% of the overall gilt sales. The remaining part is issued through syndicated gilt offerings,[1] or mini gilt tenders.[2]

The annual financing remit, set by the UK Treasury, outlines the gilt sales required from the DMO for the upcoming financial year. The document specifies the total amount gilt sales and the breakdown between index-linked gilts and conventional gilts in different maturity buckets. It is published every year mid-March as the financial year runs from the 1st of April until the 31st of March. Occasionally the remit is revised in April when the central governments' final net cash requirement for the previous financial year is published. Furthermore, the remit is usually revised in November or December when the UK government publishes its budget together with forecasts of public finances. The remit contains the Gilt Auction Calendar, stating the dates of the auctions in the next financial year. Furthermore, the document states the amount of gilts to be issued and the number of planned auctions in four categories. The four categories are: index-linked gilts, and three conventional gilt maturity buckets: short, medium, and long conventional gilts with 0-7, 7-15, and 15+ years to maturity. Therefore, the information in the remit gives investors an idea about the average size of the coming auctions in each category. An example for the DMO Financing Remit is displayed in Figure 2.

The DMO announces its auction plan for the next quarter on the last business days of March, May, August, and November in an operations calendar. An operations calendar is shown in Figure 3 for an example. This calendar publishes the dates of the coming auctions, mini-tenders, and syndicated issuances in the next quarter. The document also specifies the maturity year and the interest rate of the issuance. Importantly, it does not provide information about the size of the auction, contrary to the US, where approximate volumes are communicated in advance.[3] The auction announcements are published at 3:30 pm, usually on the Tuesday in the week preceding the auction. This press release contains all the pertinent information about the issuance. Importantly, this is the time investors learn the exact size of the auction. Additional information released in the statement are ISIN, SEDOL codes, coupon payments, and the terms and conditions of the auction. An example announcement of a 10-year gilt auction published on the 21st of April 2015 is displayed in Figure 4. Progress reports on the financing remit are often included in these announcements. These contain information on the remaining amount of gilts to be issued and the number of auctions to be held in the fiscal year. See Figure 5 for an example.

[1] An operation, in which a group of banks is appointed to manage the sale of a bond.

[2] Supplementary auctions, announced on short notice to satisfy emerging pockets of demand in specific gilts.

[3] See the US Quarterly Refunding Press Conference: https://home.treasury.gov/policy-issues/financing-the-government/quarterly-refunding

3.2 HIGH-FREQUENCY SURPRISES

To study the effects of debt issuance on interest rates, one can regress daily yield changes on the announced volumes. However, most of the announced new debt either covers the refinancing of maturing bonds, or finances public expenditures that are known before the announcement. In other words, a large share of new issuances is anticipated by the market, so the effects are already priced in by the time of the announcement. A second option is to use a measure of the surprise component of the announcement to use in the regression. Unfortunately, the surprises are not observable. The best available measure is the required average future auction size to meet the DMOs' financing remit. This quantity is published in the auction announcement press releases.[4] It is calculated as: $\frac{\text{Remaining gilt sales}_t}{\text{Number of auctions remaining}_t}$. One can use this as a proxy for investors expectation of the announcement and subtract it from the actual announced volume to obtain a *surprise volume* variable. This is arguably a better measure. However, investors form their expectations based on a much wider information set. Therefore, this measure is still prone to the issues listed above. This is confirmed by the fact that the series is autocorrelated, as shown in Figure B1. To overcome these difficulties and to capture unexpected changes in the supply of bonds, we opt for a high-frequency identification. Nevertheless, below we will make use of the announced volume and the surprise volume series to support the validity of our identified high-frequency bond supply shock.

We use the high-frequency identification to isolate anticipated and unanticipated policy changes, as in the monetary policy literature (Kuttner (2001)). Most similar to our application is Droste et al. (2021), who identify Treasury *demand* shocks by following futures price movements around the publication of US auction results. In contrast, we identify Treasury *supply* shocks by following futures price movements around announcements of bond issuance volumes. We restrict our attention to announcement days with conventional gilt announcements only (and no tenders or index-linked gilt auctions).

Data on auction announcements are sourced from the DMO. The dataset starts on the 15th of May 2001 (the date of the first announcement on the DMOs' website) and ends on the 31st of December 2019. It contains 400 auctions over 360 announcement days. As explained in Section 3.1, these announcement days are usually the Tuesdays of the week preceding the auction. Nevertheless, we match each auction with the corresponding press release available on the DMOs' website, to record the announced volume and the "surprise volume" stated in the progress report that is included in the auction announcement press release. In the few cases when the press release is not available, we use the dates and times specified in the DMOs' operations calendar and obtain the announced volumes from the auction results.

We record high-frequency gilt futures price movements around the announcements, as it is conventional in the high-frequency identification literature. Futures prices have many advantages for this application compared to spot prices or when-issued prices. Futures contracts trade on exchanges, while bonds trade over the counter. Futures are much more liquid than their cash counterparts, with better availability and data quality. Furthermore, futures markets tend to lead price discovery ahead of the spot (Garbade and Silber (1983)). We use intra-day gilt futures front contract prices to identify supply shocks, purchased from tickdatamarket.com. The contracts are traded on the London ICE exchange. There are four futures contracts written on UK government bonds: short, medium, long, and ultra-long. These can be satisfied with bonds with remaining maturities of 1.5–3.25, 4–6.25, 8.75–13 and 28–37 years, respectively. Data on short and the medium contracts are available from 2010 onward, while the long contract is available from 2001 onward. The ultra-long contract is much less liquid and we have data only between 2014 and 2016.

As described above detail in Section 3.1, the DMO releases precise information about an upcoming action usually on Tuesday of the preceding week at 3.30 pm. These occasions are the first time the DMO discloses information about the sizes of the auctions. Prior to this, investors can only speculate on the volume based on the remaining issuance volume and number of auctions left for the year. The announcements contain information about (among other things) the volume, the coupon, and the exact maturity of the upcoming issuance.[5] In other words, the announcements contain information solely about the supply side of the market. Assuming liquidity premia does not change in the narrow event window, we can interpret the price surprise as a revision in bond supply expectations. While liquidity conditions of Treasury futures are systematically priced, this liquidity premium is considered to move at lower frequencies (see Piazzesi and Swanson (2008) and Nakamura and Steinsson (2018)).

The supply shock $S_t^{(m)}$ on announcement day t in maturity segment m is measured as the difference between the (log) futures price after and before the publication of the press release. More explicitly:

[4] See Figure 5 for an example.

[5] An example announcement is displayed in Figure 4.

$$S_t^{(m)} = \left(ln(P_{t,post}^{(m)}) - ln(P_{t,pre}^{(m)}) \right) \times 100 \qquad m \in \{\text{short, medium, long, ultra-long}\} \tag{1}$$

where $P_{t,post}^{(m)}$ is the futures price 30-minutes after the announcement and $P_{t,pre}^{(m)}$ is the futures price 30-minutes before the announcement.[6]

We use the five-minute moving average of the price, to smooth out noise in the data. In cases when there was no trading activity, we use the midquote: the average of the lowest bid price and the highest ask price. We record the price difference in Equation (1) for all four futures contracts, regardless of the maturity of the bond announced. Ideally, we would like to have time series that track shifts of the supply at every maturity point of the term structure. However, we can only proxy the shifts by price movements at the four points where future contracts are available.

An illustrative example is the 10-year conventional gilt auction held on the 29th of April 2015. The exact size of the auction was published at 3:30 pm on the 21st of April (see the press release in Figure 4). The volume was £3000 million, which was 10% larger than the average auction size implied by the DMOs' progress report, published a week earlier (see the medium bucket in Figure 5). The release of this information about lower supply was followed by marked increase in the price of all futures contracts. Price movements on the 21st of April around the event window are displayed in Figure 6.

The series of the four supply shocks are displayed in Figure 7. The four $S_t^{(m)}$ series are highly correlated, so we found it convenient to compress these series into one variable by extracting the first (probabilistic) principal component. We label this series S_t without a superscript. The interpretation of S_t is an unexpected, non-maturity specific shift in the supply of government bonds. The mean of S_t is 0.001 with standard deviation of 0.132. We normalize it to have zero mean and unit variance and use it in our regression analysis as our explanatory variable.[7] The dependent variables in the regressions are daily yield changes. By moving from intraday to daily frequency, we intend to capture responses that might take longer to materialize than the one-hour length of the event window.

Table 1 reports the descriptive statistics of the supply shocks. The means are very close to zero, suggesting that the shocks are not systematic. The ultra-long contract has a positive mean, most likely due to the short sample and the low liquidity of the contract. Our results are quantitatively and qualitatively robust to omitting this contract from the analysis. We also see that the standard deviations increase with the maturity of the futures contracts.

Table 1 also shows that the series strongly co-move, with closer maturities being more correlated. However, a notable difference compared with demand shocks in other countries is the low correlation of the short-term shock with the rest. A possible explanation for this is that the number of short-term bond auctions in our sample is only 18, as the UK tends to keep a long maturity structure of its outstanding debt.[8] The supply shock series show no serial autocorrelation. The ACF of the shocks are plotted in Figure 8.

It is important to make sure that no other relevant information is released around the announcements that could contaminate the identification of the supply shock. Fleming and Remolona (1997) identifies macroeconomic news releases, monetary policy decisions and government bond auction results to be the most important drivers of Treasury yields. The DMO aims to be very transparent about releasing public announcements. Market sensitive information is usually announced between 7.30 am and 8.00 am. On auction days, the biding process closes at 10.00 am or 10.30 am, and the results are published shortly after. Post Auction Option Facility[9] results are published shortly after the end of the take-up window closure, at 1.00 pm or at 2.00 pm. For more information, see AFME (2020) or DMO (2021). Monetary policy announcements are published at 12:00, with a press conference held at 12:30. Macroeconomic data releases are published at 7:30 am or 9:00 am. Most likely, the information content of these events are already priced in at the start of our event window, at 3:00 pm.

[6] Our results are robust to both narrower and wider event window specifications. These results are available upon request.

[7] Results using the maturity specific surprises $S_t^{(m)}$ are similar and available upon request.

[8] The UK has by far the highest average term-to-maturity of outstanding marketable debt among OECD countries.

[9] Since the 1st of June 2009, all successful UK gilt auction bidders have the option to purchase up to 10-15% of the bond they have bought, at the published average auction price.

We identify the supply shock S_t as price movements within a narrow event window around announcements. The assumption is that these price movements are the equilibrium responses to underlying shifts in the supply. To verify that these market responses are related to actual changes in the supply, we link our high-frequency shock to observable movements in supply. Two available observable measures are the announced volume and the "surprise volume" series. This is calculated as the remaining planned gilt sales, divided by the number of auctions left to meet the DMOs' remit. This quantity is published in the auction announcement press release documents.

First, we regressed the announced volumes on the high-frequency supply shock S_t, but did not find significant relation between the two variables. Next, we regressed the "surprise volume" series on S_t. The estimated coefficient is significant and negative, implying that higher-than-expected supply is associated with a decrease in the futures price within the event window. Table 2 displays these results in the left column. The right column reports the results when we use a one-day event window as in Phillot (2021), instead of the one-hour window of S_t. The insignificant coefficients imply that using a narrower event window captures better the price movements that are related to the surprise component of the announced volumes. Furthermore, a regression of the daily surprise on the intraday surprise (reported in Table 3) yields a very low R^2, suggesting that there must be other important drivers of prices on announcement days, other than the press release. These results underline our argument to use intraday supply shocks instead of daily supply shocks.

4 Bond supply effects on the term structure of interest rates

4.1 EFFECT ON NOMINAL AND REAL YIELDS

To assess how unexpected shifts in the supply of bonds affect interest rates, we regress the elements of the term structure on the supply shock S_t:

$$\Delta R_t^{(m)} = a^{(m)} + b^{(m)} S_t + \varepsilon_t^{(m)} \tag{2}$$

Where $\Delta R_t^{(m)} = R_t^{(m)} - R_{t-1}^{(m)}$ is the change in the Bank of England zero-coupon-curve at maturity m relative to the previous day. The coefficients of interest are the estimated $b^{(m)}$, which capture the effect of the supply shock on the term structure.

The responses to an unexpected standard deviation increase in the (non-maturity-specific) supply of government bonds are displayed in Figure 9. The blue line shows that an increase in the supply of bonds raises nominal interest rates between 1 and 1.5 basis points. Rates at longer maturities respond stronger, implying an increase in the slope of the yield curve. The effect persists in benchmark rates until the next week, when the announced auction takes place (see Figure 10). The magnitude of the effect is similar to the responses to the demand shock, found by Droste et al. (2021) in the US and Lengyel and Giuliodori (2022) in Germany and Italy. The effect is also consistent with the findings of Phillot (2021), who estimates the effects of US Treasury supply shocks in an instrumental variable (IV) setting. Figure B2 in the Online Appendix presents similar IV results, where S_t is instrumented by the announced volume made on day t and the "surprise volume", as described in the previous section. Both the point estimates and the estimation uncertainty are slightly higher, but generally in line with the results of Figure 9. Our results are also robust to adding control variables, such as the short-term interest rate and inflation (implied by the model in Section 4.3) or weekday dummies.[10]

To offer some intuition on the size of this effect, we provide a back-of-the-envelope calculation on a fiscal expansion announcement during the Covid-19 pandemic. On March 11, 2020, the UK government announced a fiscal stimulus package of £12bn.[11] We can translate this quantity into a high-frequency futures price surprise, using the regression results of Table 2. Then, we can obtain an estimate of the reaction of the term structure to an unexpected change in the supply of bonds of the size of the package with the help of the results in Figure 9. The estimates imply that an unexpected £12bn issuance of nominal bonds would be associated with a $12 \times -0.15 = -1.8$ change in the bond futures price, a roughly 13 standard deviation event. This in turn would increase nominal yields by around $13 - 19$ basis points. The actual changes in nominal zero coupon long-term yields were between 3.7-13.8 basis points on the day of the announcement. It is important to note, however, that our calculation assumes that the announced package was unanticipated and financed entirely by new debt issuance. In reality, the announcement was at least partially anticipated and discussed in the press.[12] Nevertheless, our estimates are roughly in line with actual yield changes, even though the calculation is a huge out-of-sample exercise. This estimated effect is broadly in line with the results found by the US survey of Gale and Orszag (2003). They conclude that the effect of a sustained 1% increase in projected budget deficit raises interest rates by 20-60 basis points. To translate this into dollar terms, this would mean that a $14bn increase in the deficit raises interest rates by 2-6 basis points. We note, however, that these studies are conducted mostly at a much lower frequency, making it harder to justify the exogeneity assumption in the regressions.

What is the reason behind the reaction of the yield curve? Ang, Bekaert and Wei (2008) finds that about 80% of the variations in nominal yields are attributable to changes in expected inflation and the inflation risk premium. The sum of the two is called the inflation compensation (Bekaert and Wang (2010)), the additional return investors require for being exposed to inflation. To

[10] These results are available upon request.

[11] See: https://www.gov.uk/government/speeches/budget-speech-2020.

[12] See: https://www.reuters.com/article/uk-britain-sterling-close-idUKKBN20W2IV.

assess if the reactions in nominal yields are due to a change in the inflation compensation, we regress the elements of the *real* term structure of the Bank of England on S_t. The real term structure is constructed using inflation-linked bonds and available at maturities over 25 months. The spread between a (comparable maturity) nominal and inflation-linked bond is called the breakeven inflation rate. This is a market-based measure of the inflation compensation. Figure 9 shows the response of real rates in red, and the response of breakeven rates in grey. Real rates react with increases of 1-1.2 basis points, implying 0-4 basis points increases in breakeven rates. Inflation swap rates, another market-based measure of inflation compensation, show similar responses (see Figure B3 in the Online Appendix).[13].

These results imply that the reason behind the reaction of nominal yields to the supply shock is not a change in investors' inflation outlook. Therefore, to get a better understanding of the transmission of the shock, we break down nominal yields into its components in the next section, and analyse how each component reacts to the shock.

4.2 SUPPLY EFFECTS ON EXPECTED SHORT RATES AND RISK PREMIA

According to the expectations hypothesis, the strong response of long-term rates could be the result of either higher expected future short rates or higher risk premia. Using quarterly data and recursive identification, Dai and Philippon (2005) found risk premia to account for one third of the reaction of long-term rates to a shock to the fiscal deficit. Laubach (2011) found that fiscal deficits mostly affect the short rate and inflation, with little movement in risk premia. Similar investigations in the empirical monetary policy literature suggests that monetary policy shocks primarily influence expected short rates, with some effect on term premia at longer horizons (Hanson and Stein (2015), Abrahams et al. (2016), Nakamura and Steinsson (2018)). To get a better understanding of why government debt issuance affects interest rates, we decompose yields into the average expected nominal short rate and the nominal term premium. Then, to shed light on the role of inflation, we further decompose the nominal short rate into the real short rate and expected inflation, and the nominal term premium into real term premium and inflation risk premium. We assess how each term is affected by the supply shock.

4.2.1 DECOMPOSING NOMINAL AND REAL YIELDS

We use an affine term structure model (ATSM) to jointly price nominal and inflation-linked bonds, following Abrahams et al. (2016).[14] Several papers conducted this type of analysis in the context of monetary policy and analysed how high-frequency monetary policy surprises affect the expectations and risk premium components of yields (see Abrahams et al. (2016), Nakamura and Steinsson (2018), Tillmann (2020) and Kaminska, Mumtaz and Šustek (2021)). This paper, on the other hand, relates more to fiscal policy and traces the effects of high-frequency bond supply shocks.

The model assumes that bond yields and the market price of risks are affine functions of the state variables, which are assumed to be observable. Hence, the log prices of a nominal ($P_t^{(\tau)}$) and an inflation-linked ($P_{t,R}^{(\tau)}$) zero-coupon risk-free bonds with remaining time to maturity τ follows:

$$\log P_t^{(\tau)} = A_\tau + B_\tau' X_t$$
$$\log P_{t,R}^{(\tau)} = A_{\tau,R} + B_{\tau,R}' X_t$$

under the pricing measure, where X_t is the vector of pricing factors, assumed to follow an autoregression. Bond prices and yields are related through $y_t^{(\tau)} = -(1/n)\log P_t^{(\tau)}$ and $y_{t,R}^{(\tau)} = -(1/n)\log P_{t,R}^{(\tau)}$.

By imposing no arbitrage, expressions for the pricing coefficients $A_.$ and $B_.$ can be obtained, where the pricing coefficients are non-linear, recursive functions of the parameters driving the factors: the short rate, inflation, and the risk prices. For details of the model see Appendix A.1 and Abrahams et al. (2016) or Ang and Piazzesi (2003) and Gürkaynak and Wright (2012) for a more general treatment.

[13] Inflation swap contracts exchange a fixed rate against the realized average inflation rate at maturity. It is a market based measure of inflation compensation, which is less affected by market liquidity conditions (see ECB (2018)).

[14] For a more detailed description of this class of models see Piazzesi (2010).

A τ-period nominal bond yield can be decomposed into the average expected nominal short rate over the next τ periods and the nominal term premium $\mathrm{TP}_t^{(\tau)}$. More explicitly:

$$y_t^{(\tau)} = \frac{1}{\tau}\sum_{i=0}^{n} E_t r_{t+i} + \mathrm{TP}_t^{(\tau)} \tag{3}$$

This can be further decomposed into the average expected real short rate, average expected inflation, real term premium $\mathrm{TP}_{t,R}^{(\tau)}$ and inflation risk premium $\mathrm{IRP}_t^{(\tau)}$:

$$y_t^{(\tau)} = \frac{1}{\tau}\sum_{i=0}^{\tau} E_t(r_{t+i,R} + \pi_{t+i}) + \mathrm{TP}_{t,R}^{(\tau)} + \mathrm{IRP}_t^{(\tau)} \tag{4}$$

The interpretation of $\mathrm{TP}_{t,R}^{(\tau)}$ is the compensation investors require today to hold (real) interest rate risk for the next τ periods, while the interpretation of $\mathrm{IRP}_t^{(\tau)}$ is the compensation investors require to hold inflation risk for the next τ periods.

The elements of Equations (3) and (4) can be obtained as the following. Setting the price of risk parameters to zero, one can obtain the risk adjusted counterparts of the pricing recursion coefficients $\tilde{A}_.$ and $\tilde{B}_.$. Bond yields calculated with these coefficients are interpreted as the time t expectation of average future short rates over the next τ periods. This would be the prevailing yield if all investors were risk neutral. The difference between the risk adjusted expected nominal and the risk adjusted expected real short rate is the average expected future inflation over the next τ periods. The nominal (real) term premium can be obtained by subtracting the nominal (real) expected short rate from the fitted yield. The inflation risk premium is obtained as the difference between the fitted breakeven inflation and the inflation expectation. For more details see Appendix A.1.

The model parameters are estimated following Adrian, Crump and Moench (2013) and Abrahams et al. (2016). First, we estimate the risk neutral dynamics of the pricing factors by an autoregression. Then, we estimate the sensitivities of bond excess returns to current and past values of the pricing factors. Lastly, we do cross-sectional regressions of excess return sensitivities to lagged pricing factors onto excess return sensitivities to current pricing factors.

State variables are extracted principal components from yields. Following Abrahams et al. (2016), we extract three principal components from month-end zero coupon nominal yields and two principal components from orthogonalized real yields.[15] The factors are shown in Figure 11. The short rate is the Bank of England official bank rate, inflation is calculated with the monthly RPI index from the UK Office of National Statistics. We calculate excess returns on eleven nominal maturities of $\tau = 6, 12, 24, \dots, 120$ months and eight real maturities of $\tau = 60, 66, 72, \dots, 120$ months. In the baseline model we do not consider liquidity premium priced in inflation-linked bonds, due to the lack of a good liquidity proxy. Nevertheless, we present below a robustness exercise where we try to account for this effect. Although, according to Joyce, Lildholdt and Sorensen (2010) liquidity premium is unlikely to have had a big influence on UK yield curve dynamics over the sample period of 1992-2008.

The ATSM model parameters are estimated on monthly data from 1997-03 to 2019-12. As our goal is to decompose yields at the daily frequency, we follow Adrian et al. (2013) and use the monthly model parameters on factors extracted from daily yield curve data from 1997-03-31 to 2019-12-31 to obtain the yield decomposition at the daily frequency. Model fit diagnostics are summarized in Tables 4 and 5. The mean pricing errors are somewhat larger than in Abrahams et al. (2016), while the standard deviations are similar. Consistent with the relation between yield and return pricing errors, we find strong serial correlation in yield pricing errors but not in return pricing errors (see Adrian et al. (2013) for more details).

The fit of the model at 10-years maturity is displayed at the monthly frequency in Figure 12, and at the daily frequency in Figure 13. The decomposed 10-year expected nominal short rate and nominal term premium are displayed in Figure 14. The decomposition of the 10-year breakeven inflation rate into inflation expectations and inflation risk premium are displayed in Figure 15. The trends in the estimated 10-year nominal term premium are in line with the estimates of Bianchi, Mumtaz and Surico (2009), Malik and Meldrum (2016), Abrahams et al. (2016) and Kaminska et al. (2018). The series fluctuates close to 1% at the beginning of the sample, rising after the Global Financial Crisis and then moving into negative territory towards the end of the sample, during the asset purchase programs of the central bank. Expected inflation and inflation risk premium are close

[15] Orthogonalized yields are obtained by purging inflation-linked yields from the nominal principal components, to reduce collinearity among the pricing factors.

to the estimates of Abrahams et al. (2016), Kaminska et al. (2018) and Bekaert and Ermolov (2021). Expected 10-year average inflation is rather stable, fluctuating close to 3%. Inflation risk premium shows more variation mostly within 0-1%, dropping into negative values in the early 2000s, the Global Financial Crisis and the European debt crisis.

4.2.2 REACTION OF YIELD COMPONENTS

Which component of yields account for the strong response to the supply shock? To answer this question, we regress each components on the supply shock. First, we look at the response of the expected nominal short-term rate and the nominal term premium. Then, we further decompose yields and analyse the response of the expected short-term real rate, the expected inflation, the real term premium, and the inflation risk premium.

Figure 16 shows the reaction of the nominal term premium and the average nominal short rate to the supply shock. The response of yields is given by the sum of the yellow and the orange bars. The figure shows that a standard deviation increase in bond supply raises 10-year yields by about 1.4 basis points. Around 1-basis point increase comes from the reaction of the term premium, and 0.4 basis point increase comes from higher expected short rates. The results of Phillot (2021) are in line with this: long-term rates are more responsive to shocks, although he finds a larger response of expected nominal short rates on impact.

Next, to shed more light on the role of inflation, we further decompose yields into the expected average real short rate, the expected average inflation, the real term premium, and the inflation risk premium. The reaction of each component to the supply shock is displayed in Figure 17. It shows that most of the reaction of the nominal term premium is due to the response of the real term premium. Inflation expectations are unaffected, while the inflation risk premium displays a modest increase. In other words, additional debt issued by the government raises the compensation investors require to hold interest rate and inflation risks. Phillot (2021) finds that supply shocks raise breakeven inflation rates. Our results demonstrates that this increase is not due to the expectation component, but the risk premium component.

Apart from duration and inflation risks, the behaviour of credit risk is also of interest. Excessive debt issuance by the government can lead to debt repayment issues, raising the credit risk of the government. When markets price higher credit risk, it is reflected in higher credit default swap (CDS) rates. CDS rates can be interpreted as the insurance premium paid to insure against the default of the bond issuing entity. We asses if this is the case by regressing daily CDS rate changes written on UK Treasuries from Refinitiv on the high-frequency supply shock. Table 6 shows that increased bond supply does not have a positive effect on CDS rates, implying no increase in the credit risk of the UK government priced in CDS rates.

Next, we look at the behaviour of corporate bond yields and corporate yield spreads at various maturity buckets from Refinitiv. We found spillover effects of the government bond supply shock into corporate bond markets. Corporate bonds react strongly, with yields increasing between 0.7 and 1.5 basis points in all maturity segments.[16] Figure 21 shows the reaction of AAA, AA, A and BBB rated corporate bonds, categorized into maturity buckets of 3-5, 5-7, 7-10, 10-15 and 15+ years to maturity. Corporate bonds with better rating react more to changes in the supply of government bonds. In terms of remaining maturity, bonds that mature between 7 and 15 years have the strongest reaction to the supply shock, which is the same segment where Treasury bonds respond the most. The reaction of BBB-AAA spreads is reported in Table 7. The regression coefficients are insignificant in all maturity buckets. These results on CDS and corporate bonds imply that the repricing of credit risk is unlikely to be a transmission channel of the supply shock on interest rates.

Overall, our results imply that an important transmission channel of the effects of government debt issuance is the “risk-taking channel” (Borio and Zhu (2012)). The bond supply shock affects markets’ perception of duration and inflation risks, and this changes the equilibrium price of these risks. This is similar to the transmission of monetary policy shocks (Hanson and Stein (2015), Abrahams et al. (2016)). However, one interesting difference is that monetary policy shocks co-move negatively with the inflation risk premium, while bond supply shocks co-move positively. This is because a positive monetary policy shock is contractionary and disinflationary, while a positive bond supply shock is indicative of a more expansionary and inflationary stance of fiscal policy.

[16] At the same time, stock prices increase, and FTSE 100 index gains 0.166 (0.067) percent.

4.2.3 ADJUSTING FOR INFLATION-LINKED BOND ILLIQUIDITY

The liquidity of inflation-linked bonds and nominal bonds tend to differ, and the relative liquidity seems to be systematically priced (Pflueger and Viceira (2016)). According to Joyce et al. (2010), the liquidity premium is unlikely to have had a big influence on UK yield curve dynamics over the sample period of 1992-2008 and therefore ignores it (together with Evans (1998), Risa (2001), Abrahams et al. (2016) and others). Pflueger and Viceira (2016) find the UK liquidity risk premium to be low, around 50 basis points on average and decreasing over time. Kaminska et al. (2018) estimate it to be low prior to the crisis, jumping to 80 basis points during the GFC and gradually declining to around 20 basis points by 2014. Bekaert and Ermolov (2021) find it to be higher, close to 1% and stable.

If inflation-linked bond relative liquidity effect is priced, it can contaminate our inflation-related indicators, as they are derived using the spread between nominal and inflation-linked bonds. Therefore, we attempt to account for this effect by expanding the state space X_t, by including a liquidity factor L_t (see Abrahams et al. (2016)). Working at the daily frequency substantially reduces the number of potential liquidity proxies to use. We follow Pflueger and Viceira (2016), Kaminska et al. (2018) and Bekaert and Ermolov (2021) and use the 5-year inflation-swap spread ISS_t^{5Y} as our liquidity proxy. This is constructed as the difference between the inflation swap rate ISR_t^{5Y} and the breakeven inflation rate $ISS_t^{5Y} = ISR_t^{5Y} - (y_t^{5Y} - y_{t,R}^{5Y})$. Liquidity premium in inflation swap rates is considered to negligible, therefore, the rates only represent expected inflation and inflation risk premium (see ECB (2018) and Bekaert and Ermolov (2021)). In the absence of liquidity risk premium in breakeven rates, the spread between the swap rate and the breakeven rate should be zero. We standardize and add to each observation the negative of the minimum of the series to ensure positivity of the index. Then, before calculating inflation-related variables in the model, we subtract the effect associated with L_t from the yields.

The availability of inflation swap data is from the 29th of June 2007 to the 31st of December 2019, and it is displayed in the bottom right panel of Figure 11. It shows a steep increase during the financial crisis and elevated levels during the European debt crisis. The ATSM implied 10-year liquidity adjusted breakeven inflation, expected average inflation and inflation risk premium are displayed in Figure 18. The adjusted series show some differences compared to the model without L_t: the breakeven rate and the average expected inflation are slightly higher, and the expected average inflation shows more variability.

We repeat the analysis of the previous section and Figure 19 reports that almost all of the reaction in yields are attributed to movements in the nominal term premium once we account for liquidity effects. Figure 20 shows that the reaction of the real term premium dominates with some effect on inflation risk premium. The expectation components only react at short horizons. Expectation variables in the ATSM model are the risk-neutral yields and breakevens, calculated by setting the risk prices to zero. Quantifying the price of liquidity risk and setting it to zero results in short rate expectations to be much less responsive to the supply shock.

To summarize, our results suggest that changes in government debt issuance affects predominantly the risk premia component of yields. When investors are faced with higher supply of government bonds, they require higher compensation for holding interest rate and inflation risks. In the next section, we examine this effect through the lens of an equilibrium term structure model. The aim of the model is the illustration of the effect rather than providing a complete structural explanation of the mechanism.

4.3 A TERM STRUCTURE MODEL OF NOMINAL AND REAL BONDS WITH SUPPLY EFFECTS

The main finding of our empirical analysis is that additional supply of nominal bonds raises nominal and real yields, mostly due to increases in risk premia. As the government issues more debt, investors require higher compensation to hold interest rate and inflation risks. We illustrate these findings in a theoretical framework, building on the Greenwood and Vayanos (2014) version of the Vayanos and Vila (2021) model. This section provides the intuition for the mechanism, while the complete model is spelled out in Section A.2 in the Appendix.

We extend the Greenwood and Vayanos (2014) model with inflation risk and include two types of bonds: a continuum of nominal bonds and a continuum of inflation-linked bonds. These are supplied by the government in a price inelastic manner. Marginal investors in the model are short-lived risk averse arbitrageurs. These arbitrageurs absorb shocks to the supply of bonds and

ensure that the term structure of interest rates is smooth and arbitrage free. They require additional return for holding the bonds compared to the risk-free short rate, as unexpected shocks can result in the bonds underperforming relative to the short rate.

To the best of our knowledge, there are two papers with similar setups. Saúl (2012) derives the breakeven inflation rate in a model with preferred-habitat investors, as in Vayanos and Vila (2021). Bond prices are determined through the interaction between arbitrageurs and preferred-habitat investors. Preferred-habitat demand for bonds is non-stochastic. This in contrast to our setup of exogenous bond supply, which is subject to shocks. Our focus is specifically on this additional stochastic risk factor, and we analyse how equilibrium bond prices are affected by this supply risk.

Diez de los Rios (2020) constructs a discrete-time version of the Greenwood and Vayanos (2014) model, with both nominal and real bonds in fixed supply. Inflation is endogenous, determined by a Taylor-rule type equation. The focus is on demonstrating how an increase in the bond supply can lead to higher inflation. Our continuous time model has exogenous inflation, with the aim to illustrate how additional bond issuance transmits to yields, by altering the price of inflation and duration risks.

Bond yields in the model in Section A.2 react positively to the supply shock, with the effect stronger at long-horizons, just like in our empirical results. The supply shock raises both the duration risk premium and the inflation risk premium. Furthermore, we also find a positive relation between the supply shock and the breakeven inflation rate. The intuition is the following. In equilibrium, risk prices are increasing in the sensitivity of investors' portfolio to the risk factors. Expected excess returns of bonds are, therefore, also increasing in this sensitivity. As the outstanding amount of nominal bonds increases, the amount of duration and inflation risks borne by arbitrageurs also increases. Higher sensitivity of their portfolio to the risk factors raises the price of these factors and the risk premiums. This in turn raises the term premium and the inflation risk premium, raising bond yields. As inflation-linked bonds are free from inflation risk, their yield does not rise as much as nominal yields, resulting in higher breakeven inflation rates.

This mechanism is linked to the limited risk bearing capacity of investors. When risk aversion is high in the model, yields and risk prices become more responsive to the supply shock. In the next section, we test this prediction empirically and explore further state dependencies in the effects of the shock.

5 Non - linearities

The model in Section 4.3 suggested that the response of yields to the supply shock is higher in states when risk aversion is high. This is the same result found in Greenwood and Vayanos (2014) and Vayanos and Vila (2021). We test this non-linearity empirically. He and Krishnamurthy (2013) suggest that risk aversion is higher is a crisis and in periods of financial market stress. Therefore, we use a country-level composite indicator of systemic stress in the financial system (CISS index by Hollo, Kremer and Lo Duca (2012)), sourced from the European Central Bank. We construct a financial stress indicator variable I_t, that is equal to one when the CISS index is above its 75th percentile and zero otherwise.[17] The index is displayed in Figure 22. We estimate the state-dependent version of Equation 2, using the indicator above:

$$\Delta R_t^{(m)} = I_t\left[a_1^{(m)} + b_1^{(m)} S_t\right] + (1 - I_t)\left[a_0^{(m)} + b_0^{(m)} S_t\right] + \varepsilon_t^{(m)} \quad (5)$$

The findings are reported in Figure 23. In normal times a standard deviation supply shock raises nominal yields up to 1.2 basis points. On the other hand, during market stress periods the reaction is as high as 1.9 basis points at long maturities. The reason behind this is that in turbulent times, the term premium becomes much more responsive to the supply shock. Long-term bonds are more sensitive to risks and market stress periods are characterized by a steep increase in risk prices. This is consistent with the findings on Treasury demand shocks, which are documented to have stronger effects in times of market stress (Droste et al. (2021), Lengyel and Giuliodori (2022)).

The preferred-habitat theory of bond yields by Vayanos and Vila (2021) and Droste et al. (2021) predicts that when risk aversion is low, demand shocks affect interest rates similarly across the maturity space. However, when investors' risk aversion is high, a shock at a specific maturity segment has more concentrated effects at nearby maturities. We test this prediction, by first restricting the announcements sample to only include announcements of short- and medium-maturity bonds (0-15 years according to the DMOs' classification) and estimating Equation (2). Then, we restrict the announcements sample to only include announcements of long-maturity bonds (15+ years) and estimate again Equation (2). The results are reported in Figure B4. It shows that when markets are calm, the effect of the shock is similar across maturities. However, when markets are under stress, short- and medium-maturity bond announcements have a larger effect on the short end of the yield curve, while long-maturity bond announcements have a larger effect on the long end of the curve.

Next, we analyse other non-linearities in the effects of the supply shock, inspired by results in the fiscal policy literature. Previous studies found that the effects of fiscal policy depend on the state of the business cycle Auerbach and Gorodnichenko (2012) and that the effects are stronger when monetary policy is at the effective lower bound (ELB) (Christiano et al. (2011)).[18] Therefore, we construct dummy variables that indicate if the economy is under one of these conditions. We collect monthly unemployment rate data from the Office for National Statistics, and the policy rate from the Bank of England. We construct an indicator of high unemployment, that takes the value one when unemployment is above its long-term mean of 6.81%, and zero otherwise. The ELB indicator takes the value one when the policy rate is below 0.5%, and zero otherwise. Figure 22 shows the time series of these indices. The correlation among them is high, therefore, we cannot disentangle with certainty which non-linearity is at play in our results.

When unemployment is above its long-term mean, long-maturity bonds react stronger and short-maturity bonds react weaker to the supply shock. At the same time, the term premium is much more responsive than the expected short rate (Figure 24). This weak reaction of short rates could be due to the fact that in our sample, high-unemployment periods often coincided with periods with the policy rate constrained by the lower bound. When we split our sample to periods where the Bank of England policy rate was below 0.5%, and periods when it was above. These results are displayed in Figure 25. They show that short-term interest rates are much less responsive, while long-term interest rates are more responsive during ELB periods. As previously, this reaction is because in the ELB regime the term premium component is much more affected by the supply shock, while the expectation component is less responsive to the shock. Results are reported in Figures 24-23.

[17] Our results are robust to a wide range of this threshold and they are available upon request.

[18] We did not find differences in the effect of the supply shock based on the sign of the shock, contrary to the findings of Barnichon, Debortoli and Matthes (2022).

In summary, when economic or financial conditions are adverse, the term premium and the inflation risk premium are more responsive to a change in the supply of government debt. This affects long-term bonds, and the slope of the yield curve in particular. Long-term yields are more exposed to risks and during unfavourable economic conditions investors require a higher compensation for their exposure to risks. Furthermore, in states of high risk aversion, signs of bond market segmentation can be observed.

6 Conclusion

In this paper, we identify government bond supply shocks by recording intraday price movements around government bond auction volume announcements. We apply this high-frequency identification to the UK Debt Management Offices announcements and studied how additional debt issuance affects the term structure of interest rates. We found that a standard deviation bond supply shock increases nominal yields by 1-1.5 basis points. Real rates raise by 1-1.2 basis points, implying a modest reaction of the inflation compensation.

To study the transmission of the shock, we decomposed yields into expected short rates and the risk premia. We found that the shock mostly affects the risk premia components, with smaller effects on future expected average short-term rates and no effect on expected inflation. Both the real term premium and the inflation risk premium react positively to higher bond supply. We reconciled these results in an equilibrium term structure model, where risk averse investors absorb shocks to the supply of nominal bonds. Their equilibrium portfolio becomes more sensitive to duration and inflation risks, driving up the price of these risk factors. This in turn raises risk premia and yields. As inflation-linked bonds are unaffected by inflation risk, the breakeven inflation rate goes up.

A prediction of the model is that when risk aversion is high, the effect of the supply shock is more pronounced. In line with this, during times of financial market stress we found stronger reactions of yields to the high-frequency supply shock. The increase is driven by higher risk premia, consistent with the equilibrium model. We found similar results in periods of high unemployment and when the policy rate is at the effective lower bound.

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Figures

Figure 1
Composition of UK central government sterling debt in December 2019

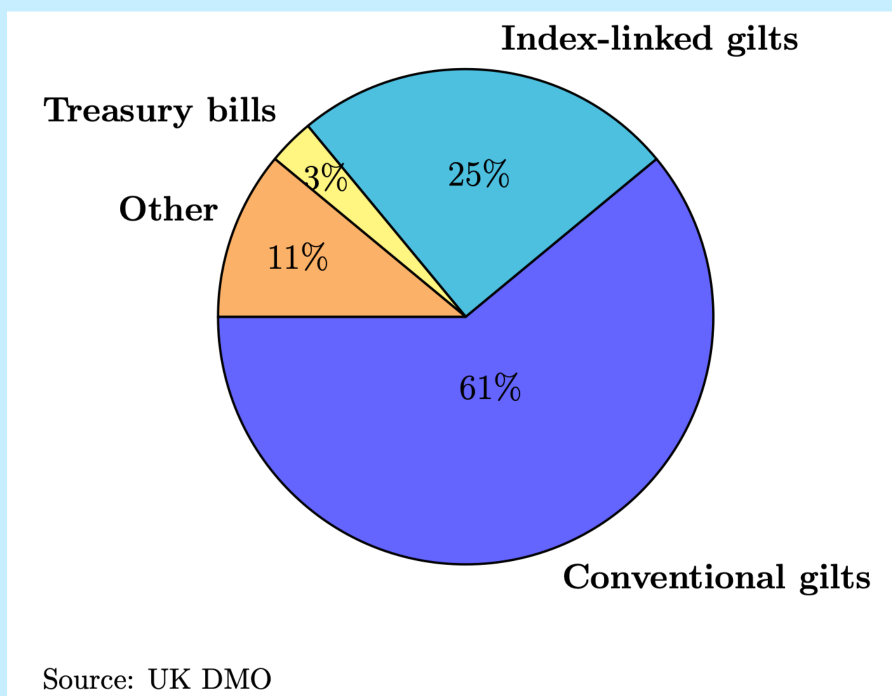

Figure 2
DMO Financing Remit for the 2015-16 financial year, published the 18th of March 2015

DMO FINANCING REMIT 2015-16: 18 MARCH 2015

1. The DMO's financing remit for 2015-16 has been published today as part of the Budget 2015 announcements. The main points are summarised below.

A) Debt issuance by the DMO

2. The DMO plans to raise £140.4[1] billion in 2015-16, split as follows:

- Outright gilt sales: £133.4 billion.
- Net Treasury bill sales (via tenders): £7.0 billion.

B) Planned gilt sales

3. It is intended that the gilt sales plans will be met through a combination of:

   - £105.2 billion of issuance in 39 auctions; and
   - additional supplementary gilt sales of £28.2 billion (21.1% of total issuance) via a combination of syndicated offerings and, subject to demand, mini-tenders. This will comprise a minimum £24.2 billion via a syndication programme. Any additional sales via syndication can only be of long conventional or index-linked gilts but mini-tenders can be used for issuance of conventional and index-linked gilts across the curve.

4. The planned split of issuance by maturity and type of gilt to be sold via auctions and syndicated offerings is as follows:

   Conventional:

   Short: £33.9 billion (25.4%) in 8 auctions

   Medium: £26.7 billion (20.0%) in 8 auctions

   Long: £37.4 billion (28.0%) in 12 auctions and via syndicated offerings (aiming to raise £28.1 billion by auctions and a current planning assumption of a minimum of £9.3 billion via syndication).

   Index-linked: £31.4 billion (23.5%) in 11 auctions and via syndicated offerings (aiming to raise £16.5 billion by auctions and a current planning assumption of a minimum of £14.9 billion via syndication).

5. The issuance methods to achieve the syndication and mini-tender plans are based on current assumptions. In particular, total financing achieved through each supplementary issuance method will be dependent on market and demand conditions at the time transactions are conducted.

[1] Sales figures in this announcement are in cash terms unless otherwise indicated.

Figure 3
Gilts Operations Calendar for April-May 2015, published the 31st of March 2015

United Kingdom
Debt Management
Office

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London
EC3M 8UD

T 020 7862 6500
F 020 7862 6509

www.dmo.gov.uk

31 March 2015

PRESS NOTICE

GILT OPERATIONS CALENDAR: APRIL- JUNE 2015

PLANNED SYNDICATED OFFERING OF AN INDEX-LINKED GILT WITH A MATURITY IN THE 30 YEAR AREA OR LONGER IN JUNE 2015

The UK Debt Management Office ("the DMO") is announcing today that the first syndicated offering of the 2015-16 programme will be the sale of an Index-linked gilt with a maturity in the 30 year area or longer. The DMO expects that, subject to market conditions, the sale will take place in the second half of June 2015. Further details of the sale, including the composition of the syndicate, will be announced in due course.

The DMO also announces that in the period April-June 2015 it plans to hold ten outright gilt auctions as well as the syndicated offering, as set out below.

Auction date	Gilt	Further details announced[1]
Wednesday 8 April	2% Treasury Gilt 2020	Tuesday 31 March
Thursday 16 April	0⅝% Index-linked Treasury Gilt 2040	Tuesday 7 April
Tuesday 21 April	3½% Treasury Gilt 2045	Tuesday 14 April
Wednesday 29 April	2% Treasury Gilt 2025	Tuesday 21 April
Thursday 14 May	2% Treasury Gilt 2020	Tuesday 5 May
Thursday 21 May	4¾% Treasury Gilt 2030	Tuesday 12 May
Wednesday 27 May	0⅛% Index-linked Treasury Gilt 2058	Tuesday 19 May
Tuesday 2 June	2% Treasury Gilt 2025	Tuesday 26 May
Tuesday 9 June	0⅛% Index-linked Treasury Gilt 2024	Tuesday 2 June
Thursday 11 June	3½% Treasury Gilt 2045	Tuesday 2 June

[1] Further to the announcement on 29 January 2015, as of 31 March 2015 the DMO will no longer be declaring a "When Issued" (WI) trading period in cases where the stock being auctioned is a re-opening of an existing line of gilts with a pre-existing ISIN code. Accordingly, the DMO will no longer be issuing a separate WI ISIN code for new tranches of existing gilts. The 29 January announcement can be found at: http://www.dmo.gov.uk/documentview.aspx?docName=/gilts/press/sa290115.pdf

Figure 4
Auction announcement of the auction of £3,000 million of 2% Treasury Gilt 2025, published the 21st of April 2015

United Kingdom
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www.dmo.gov.uk

21 April 2015

PRESS NOTICE

AUCTION OF BRITISH GOVERNMENT STOCK

Auction Details

Auction Date	Wednesday, 29 April 2015
Issue and Settlement Date	Thursday, 30 April 2015
Bidding Convention	Fully paid Bid Price (see Note 1)
Accrued Interest payable with bid	£0.222826 per £100 nominal
Auction Close	10:30am London Time

Details of Security

Title	2% Treasury Gilt 2025
Amount (nominal) for auction	£3,000 million (fungible with previous issue) (see Note 4)
Nominal outstanding after auction	£6,024.9 million
Maturity Date	7 September 2025 at par
Interest Dates	7 March – 7 September
ISIN Code	GB00BTHH2R79
SEDOL Code	B-THH-2R7
Strippable	From 30 April 2015 (see Note 2)
Interest Payable	Gross (see Note 3)
Next Interest Date	7 September 2015 - £0.929348 per £100 nominal (Short First Coupon)

Note 1: Bids may be made on either a competitive or a non-competitive basis. Details of the bidding procedures are set out in the prospectus and in the Information Memorandum. Gilt-edged Market Makers may bid by means of the Bloomberg Bond Auction System to the DMO not later than 10.30 am on Wednesday, 29 April 2015.

Note 2: Following the issue of this further amount of the Gilt, 2% Treasury Gilt 2025 may be stripped and holdings of the Gilt reconstituted: the provisions relating to strips contained in the Information Memorandum will therefore apply except that the minimum stripping unit will be £1,000,000 nominal until the payment of the non-standard first coupon on 7 September 2015. The SEDOL and ISIN codes for the new principal strip are B-WXB-PL9 and GB00BWXBPL93 respectively.

Note 3: Holders may elect to have United Kingdom income tax deducted from interest payments, should they so wish, on application to the Registrar, Computershare Investor Services PLC.

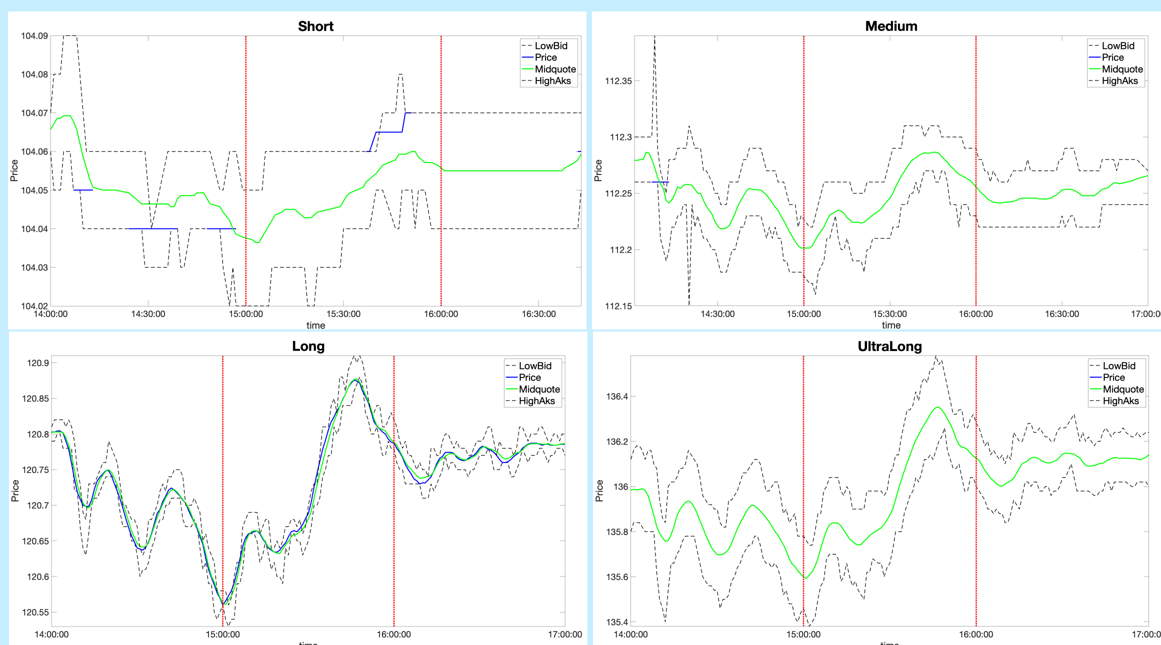
Figure 5
A progress report of the 2015-16 Financing Remit, published on the 14th of April 2015

Remit 2015-16

Gilt sales of £133.4 billion (cash) are planned in 2015-16 and progress against the remit is summarised in the table below (which may not include the amount of gilts issued under the Post Auction Option Facility for the most recent auction, if any).

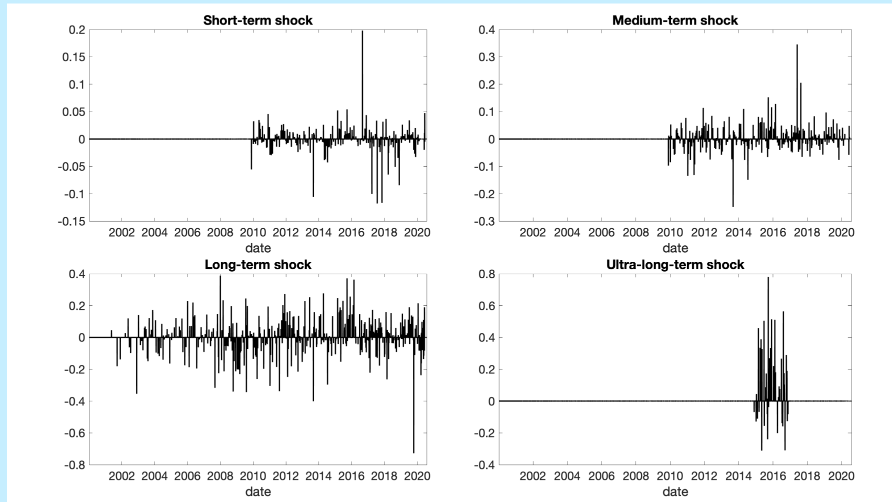
Gilt sales relative to remit plans 14 April 2015 (£ millions)					
	Conventional Gilts			Index-linked gilts	Total
	Short	Medium	Long		
Auction proceeds to-date	4,166	0	0	0	4,166
PAOF proceeds to-date	10	0	0	0	10
Auction and PAOF proceeds to-date	4,177	0	0	0	4,177
Syndication sales to-date	0	0	0	0	0
Mini-tender sales to date	0	0	0	0	0
Total gilt sales to date	**4,177**	**0**	**0**	**0**	**4,177**
Auction sales required to meet plans	29,723	26,700	28,100	16,500	101,023
Number of auctions remaining	7	8	12	11	38
Currently required average auction sizes	4,246	3,338	2,342	1,500	
Planned gilt sales at auctions	**33,900**	**26,700**	**28,100**	**16,500**	**105,200**
Number of auctions scheduled	8	8	12	11	39
Minimum syndication sales plan	0	0	9,300	14,900	24,200
Syndication sales required to meet minimum plan	0	0	9,300	14,900	24,200
Balance of supplementary gilt sales					28,200
Total planned supplementary gilt sales					**28,200**
Total planned gilt sales					**133,400**

Figure 6
Futures price movement around the event window on the 21th of April 2015



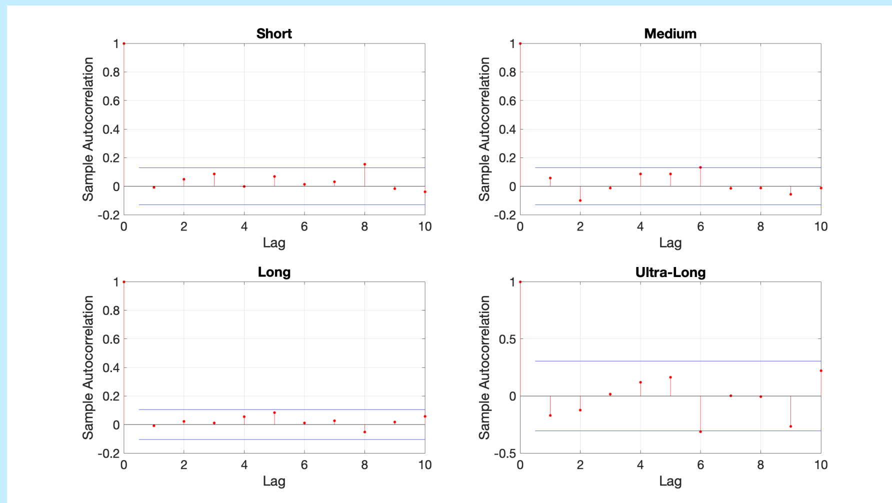
Note: Red lines denote the event window, dashed line the lowest bid and highest ask price. The green line is the 5-minutes moving average of the midquote, blue line is 3-minutes moving average of the recorded traded price, if actual trading took place. Announcements are made at 15:30.

Figure 7
Time series of the supply shocks



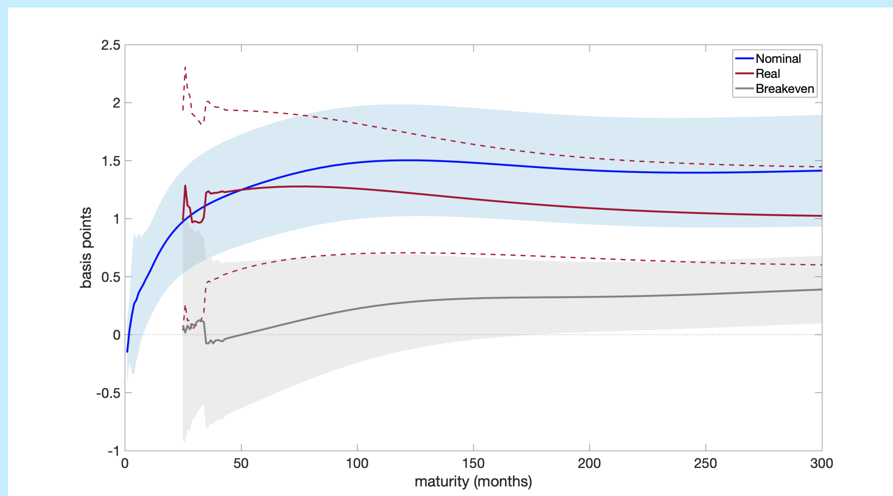
Note: Time series of S_t^{Short} (top left), S_t^{Medium} (top right), S_t^{Long} (bottom left), $S_t^{Ultra-long}$ (bottom right).

Figure 8
Sample autocorrelation function of the shock series



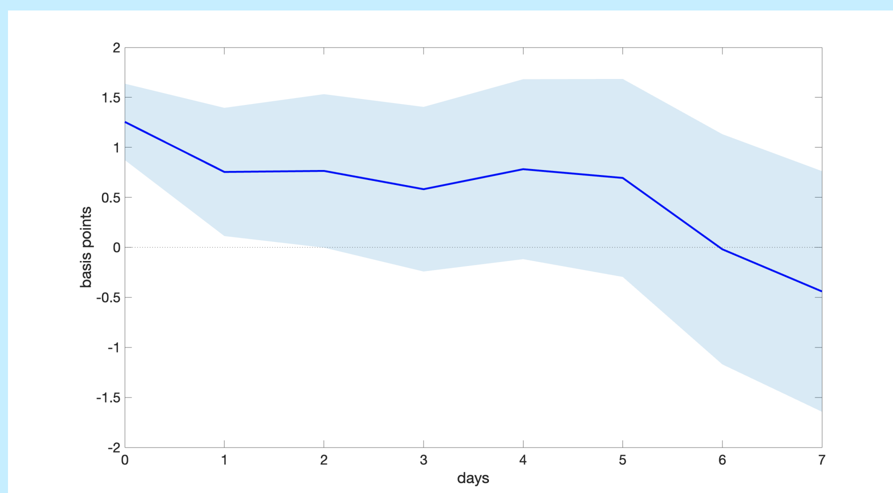
Note: Sample autocorrelation function of the shock series up to ten lags. Blue lines represents two standard errors confidence intervals.

Figure 9
Reactions of the term structure of nominal (blue), real (red) and breakeven inflation (grey) to the bond supply shock



Note: Estimated $b^{(m)}$ coefficients from equation (2). Dashed lines and shaded area are 95% (Newey-West, 10 lags) confidence intervals. Sample: 31.03.2001-31.12.2019.

Figure 10
Impulse response of the 10-year benchmark nominal rate



Note: Impulse response of 10-year benchmark rates from long difference regressions, where the dependent variable is $Y_{t+h} - Y_{t-1}$ and h are days. Shaded area are 90% Newey-West (10 lags) confidence intervals. Sample: 31.03.2001-31.12.2019.

Figure 11
Time Series of the ATSM Pricing Factors

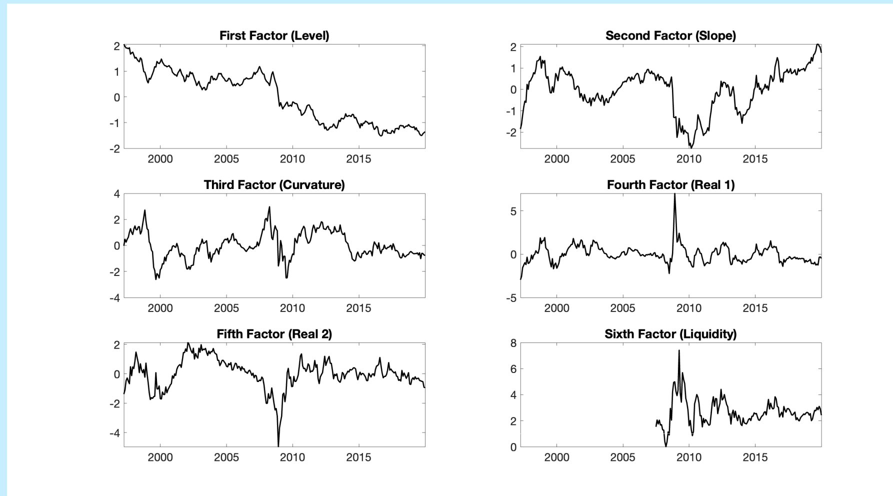


Figure 12
ATSM model fit at 10-years, monthly frequency - nominal yield (left), real yield (right)

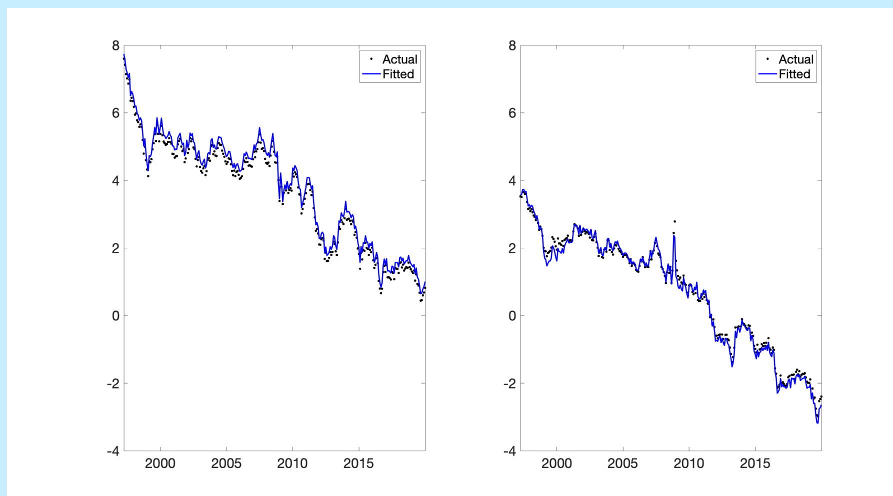


Figure 13
ATSM model fit at 10-years, daily frequency - nominal yield (left), real yield (right)

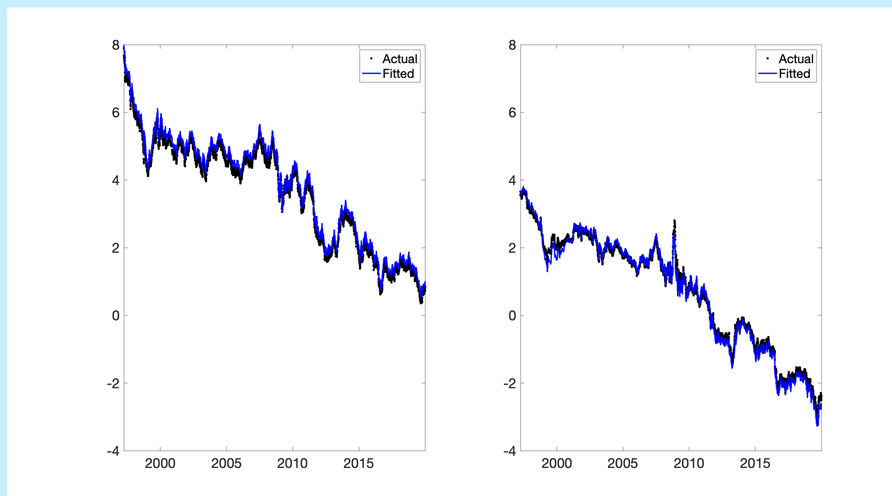


Figure 14
10-year nominal yield decomposition (left) and real yield decomposition (right) at the daily frequency

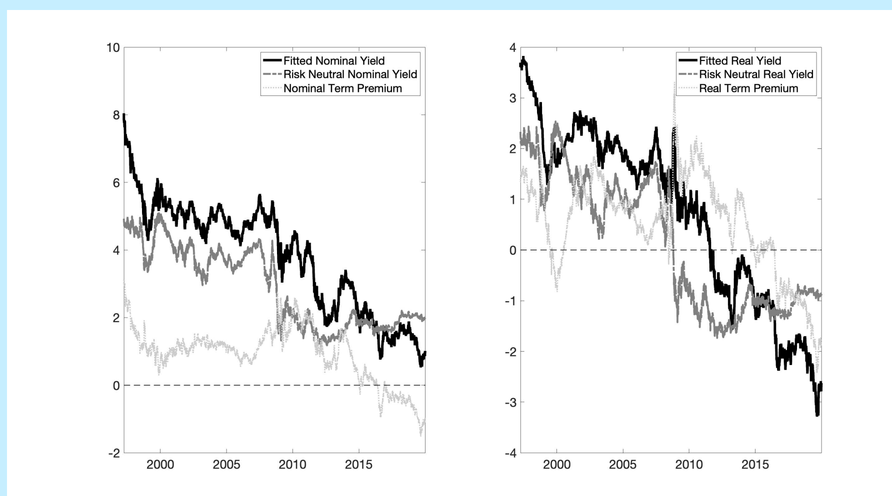


Figure 15
10-year breakeven inflation rate decomposition at daily frequency

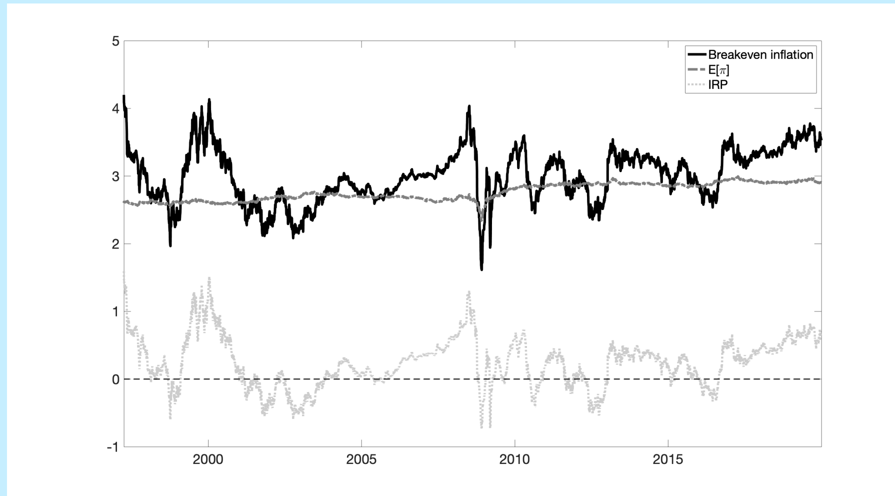
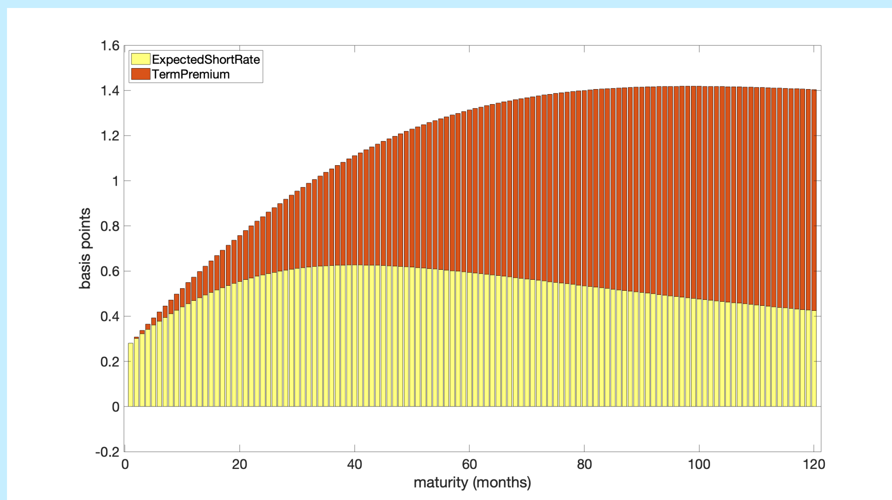
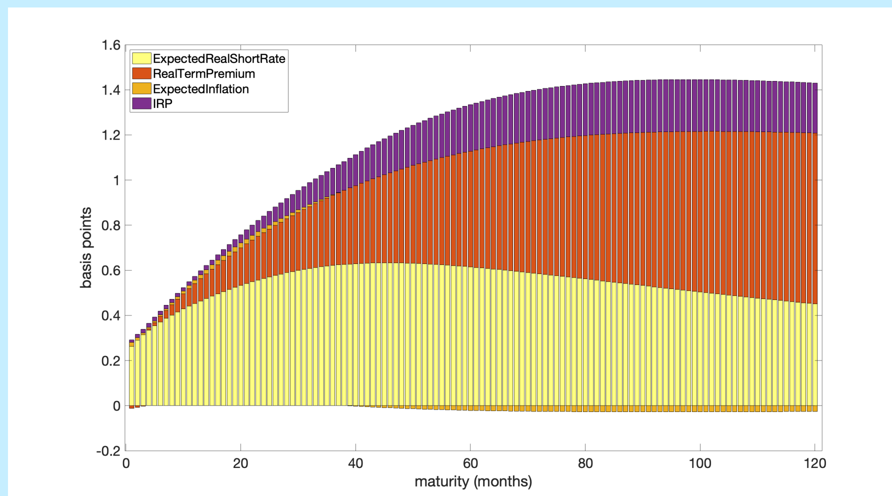


Figure 16
Reactions of the expected nominal short rates and the nominal term premium



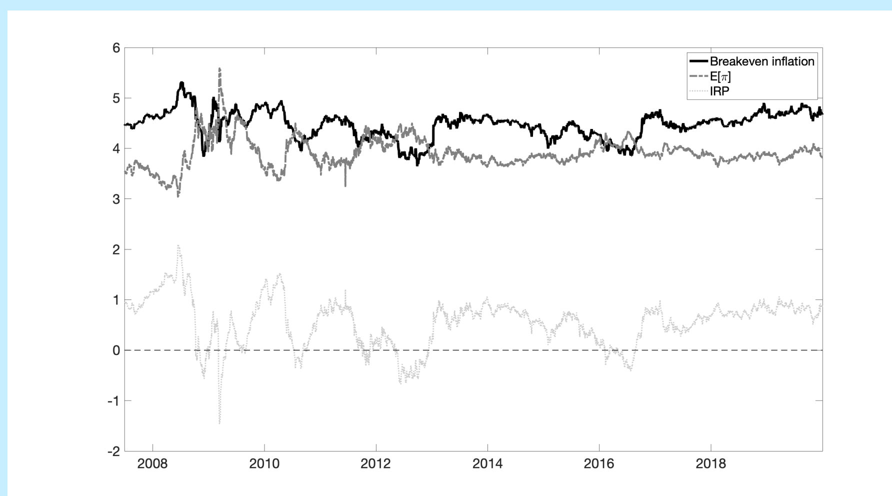
Note: Bars are the estimated $b^{(m)}$ coefficients from equation (2), where the dependent variables are the average expected nominal short rates (yellow) and the nominal term premia (red), obtained with the ATSM.

Figure 17
Reactions of the expected real short rates, real term premium, expected inflation and inflation risk premium



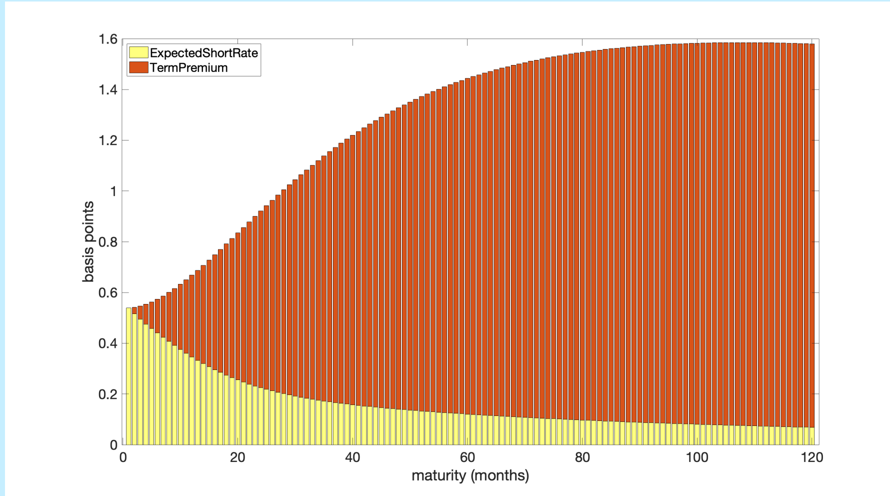
Note: Bars are the estimated $b^{(m)}$ coefficients from equation (2), where the dependent variable is the average expected real short rate (yellow), expected inflation (orange), the real term premium (red) and inflation risk premium (purple) obtained via the ATSM.

Figure 18
10-year breakeven inflation rate decomposition at daily frequency, adjusted for liquidity



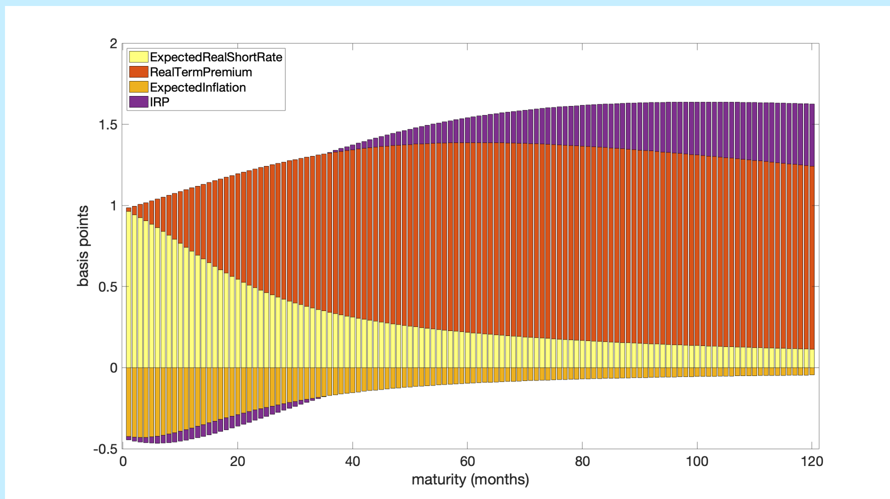
Note: Decomposition of the ATSM model implied 10-year breakeven inflation rates into expected average inflation and inflation risk premium, where the state space of pricing factors is extended with a liquidity proxy: the inflation swap, breakeven inflation rate spread.

Figure 19
Reactions of the expected nominal short rates and nominal term premium - adjusted for liquidity effects



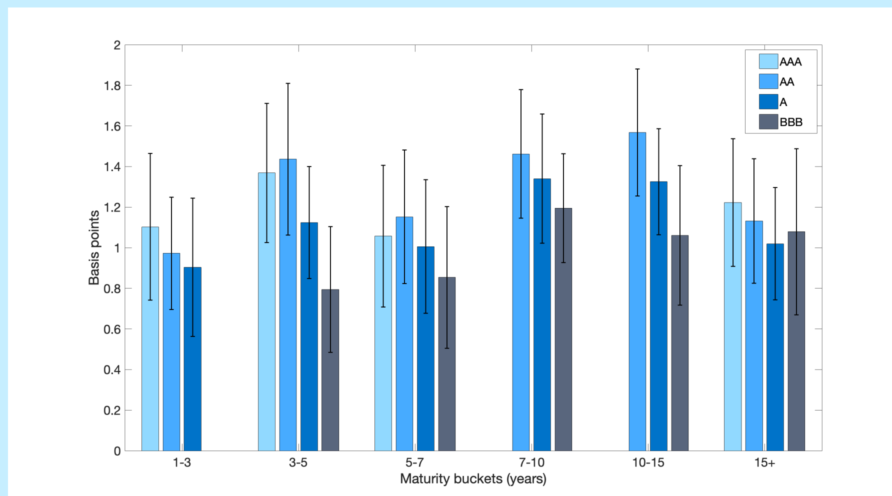
Note: Bars are the estimated $b^{(m)}$ coefficients from equation (2), where the dependent variables are the average expected nominal short rate (yellow) and the nominal term premium (red), obtained via the ATSM decomposition. The state space of pricing factors in the ATSM model is extended with a liquidity proxy: the inflation swap, breakeven inflation rate spread.

Figure 20
10-year breakeven inflation rate decomposition at daily frequency, adjusted for liquidity



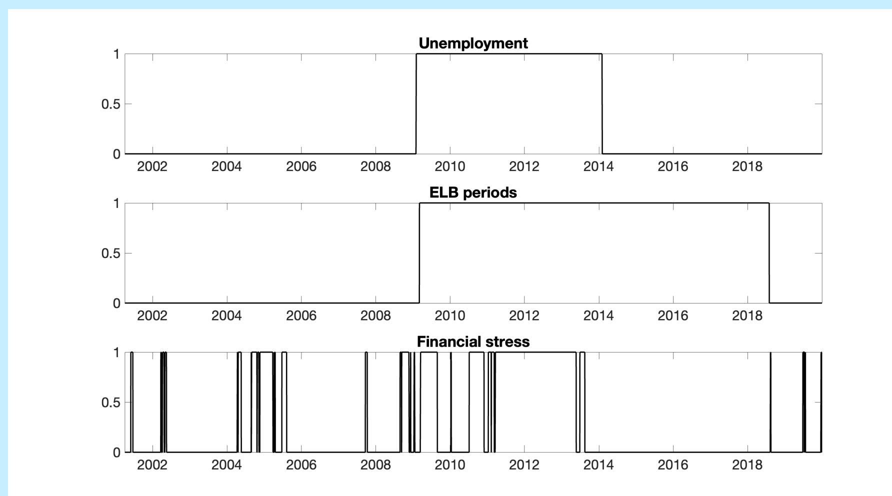
Note: Bars are the estimated $b^{(m)}$ coefficients from equation (2), where the dependent variables are the average expected real short rates (yellow), the expected inflation (orange), the real term premium (red) and the inflation risk premium (purple) obtained via the ATSM. The state space of pricing factors in the ATSM is extended with a liquidity proxy: the inflation swap, breakeven inflation rate spread.

Figure 21
Reactions of corporate bond indices to the supply shock



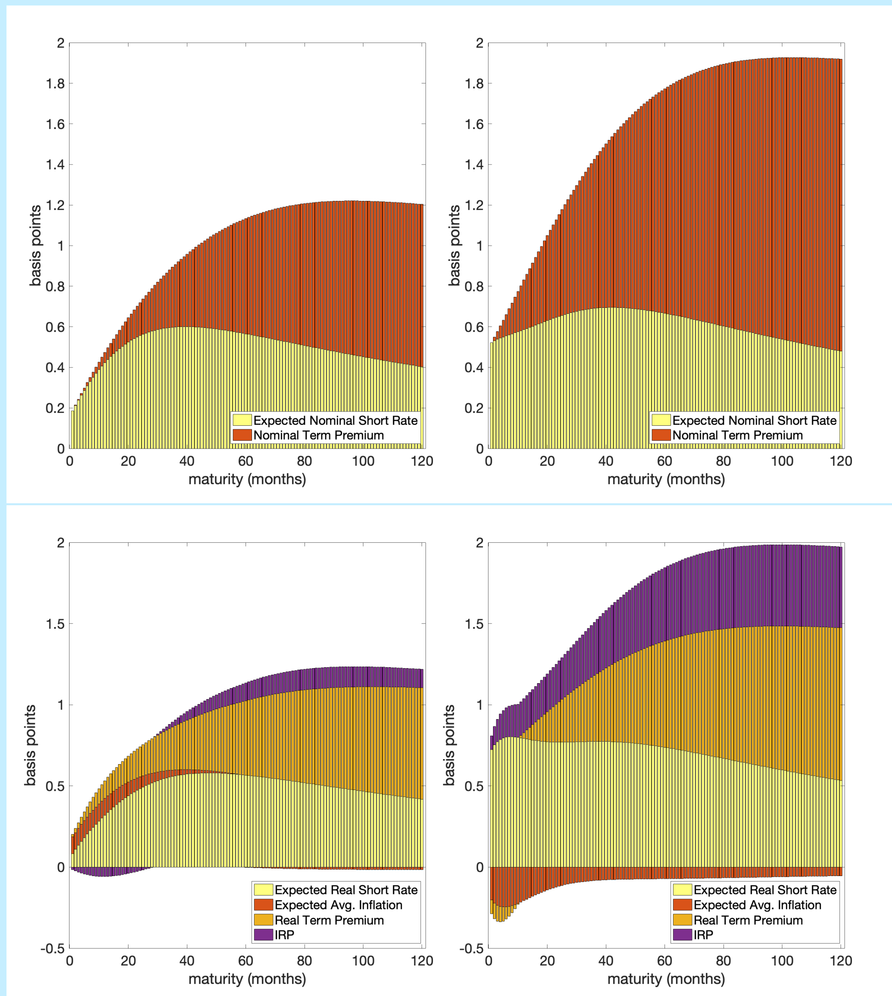
Note: Bars are the estimated $b^{(m)}$ coefficients from equation (2), when the dependent variables are AAA, AA, A and BBB rated corporate indices, with remaining maturity between 1-3, 3-5, 5-7,7-10, 10-15 and 15+ years, compiled by Refinitiv. Error bands are 95% (Newey-West, 10 lags) confidence intervals.

Figure 22
Times series of state indicators for the non-linear estimation



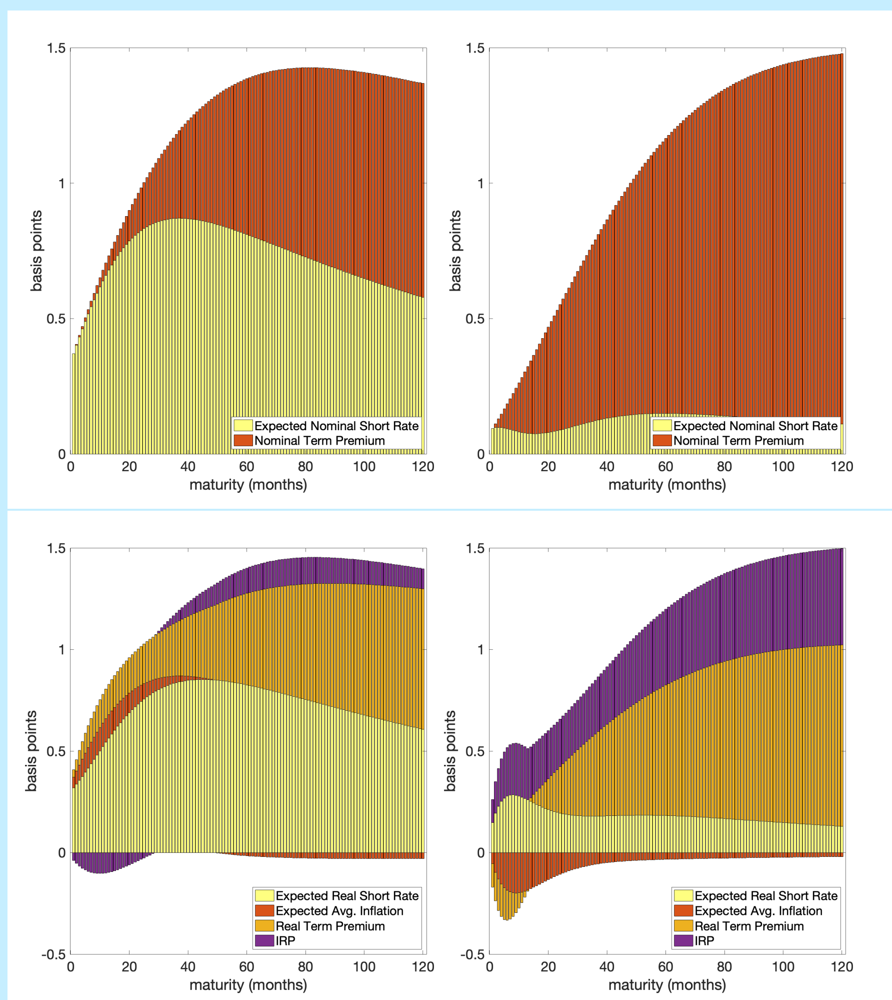
Note: Time series of the state indicator variables. The unemployment indicator takes the value one when the unemployment is above its long-term mean (6.81%). The ELB periods indicator takes the value one when the Bank of England bank rate is below 0.5%. The financial stress indicator takes the value one when the CISS index is above its 75th percentile.

Figure 23
Reactions of yield components - low stress (left), high stress (right)



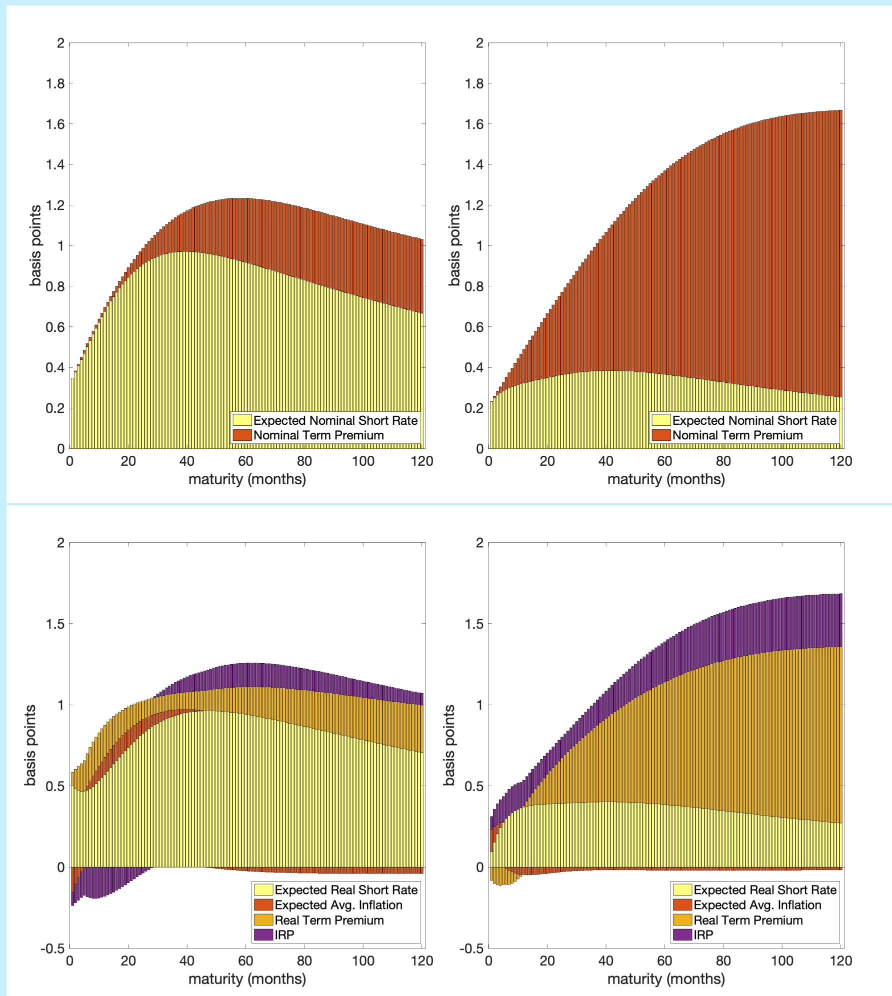
Note: Bars are estimated $b_1^{(m)}$ and $b_0^{(m)}$ coefficients from Equation 5 on yield components obtained via the ATSM. I_t indicates periods with the CISS index above its 75th percentile. Top panels: dependent variables are the average expected nominal short rate (yellow) and the nominal term premium (red). Bottom panels: the dependent variables are the average expected real short rate (yellow), the expected inflation (orange), the real term premium (red) and the inflation risk premium (purple).

Figure 24
Reactions of yield components - low unemployment (left), high unemployment (right)



Note: Bars are estimated $b_1^{(m)}$ and $b_0^{(m)}$ coefficients from Equation 5 on yield components obtained via the ATSM. I_t indicates periods with unemployment above its long-term mean. Top panels: dependent variables are the average expected nominal short rate (yellow) and the nominal term premium (red). Bottom panels: the dependent variables are the average expected real short rate (yellow), the expected inflation (orange), the real term premium (red) and the inflation risk premium (purple).

Figure 25
Reactions of yield components - non-ELB periods (left), ELB periods (right)



Note: Bars are estimated $b_1^{(m)}$ and $b_0^{(m)}$ coefficients from Equation 5 on yield components obtained via the ATSM. I_t indicates periods with the BoE Bank Rate below 0.5%. Top panels: dependent variables are the average expected nominal short rate (yellow) and the nominal term premium (red). Bottom panels: the dependent variables are the average expected real short rate (yellow), the expected inflation (orange), the real term premium (red) and the inflation risk premium (purple).

Tables

Table 1
Descriptive statistics of the high-frequency shocks

	Sample	N	Mean	Std.	Correlations				
					$S_t^{(Short)}$	$S_t^{(Med.)}$	$S_t^{(Long)}$	$S_t^{(U.long)}$	S_t
$S_t^{(Short)}$	24.11.09-31.12.19	238	-0.001	0.026					
$S_t^{(Med.)}$	24.11.09-31.12.19	238	0.004	0.053	0.271				
$S_t^{(Long)}$	15.05.01-31.12.19	360	0.001	0.125	0.293	0.949			
$S_t^{(U.long)}$	25.11.14-15.11.16	45	0.120	0.256	0.280	0.819	0.852		
S_t	15.05.01-18.02.20	360	0.001	0.132	0.311	0.959	0.999	0.853	

Table 2
Regression of the volume surprise at auctions on the high-frequency shock

	Intraday window	**Daily window**
	Panel (A): Announced volume	
Volume (bn £)	0.002	0.003
S.E.	(0.006)	(0.019)
P-value	0.709	0.883
R^2	0.000	0.000
N	314	314
	Panel (B): Surprise volume	
Surprise volume (bn £)	-0.150**	-0.082
S.E.	(0.059)	(0.202)
P-value	0.014	0.686
R^2	0.019	0.000
N	314	314

Note: Dependent variables are the high-frequency price movements in the event window on auction days. Left column: one-hour event window (S_t), right column: one-day event window. Panel (A): independent variable is the announcement volume. Panel (B) independent variable is the difference between the actual announced volume minus the implied average remaining auction size that is required to meet the DMOs' remit. Sample: 04.04.2006-31.12.2019.

Table 3
Regression of the daily surprise on the intraday surprise S_t

	Daily surprises
Intraday surprise S_t	1.110
S.E.	(0.180)
P-value	0.000
R^2	0.111
N	345

Note: Dependent variable is the price surprise on announcement days with one-day event window. Independent variable is the intraday price surprise on announcement days with one-hour event window (S_t). Sample period: 15.05.2001-31.12.2019.

Table 4
Fit Diagnostics of the ATSM model on monthly data

	n = 36	n = 60	n = 84	n = 120
		Nominal Yield Pricing Errors		
mean	0.297	0.221	-0.257	0.189
std	0.049	0.034	0.050	0.037
ρ^y	0.952	0.796	0.936	0.791
ρ^{xr}	0.220	0.129	0.048	-0.021
		Real Yield Pricing Errors		
mean		-0.110	-0.200	0.046
std		0.160	0.127	0.118
ρ^y		0.796	0.936	0.791
ρ^{xr}		0.129	0.048	-0.021

Note: Time series properties of the ATSM pricing errors implied by the monthly estimation. "Mean" and "std" refers to the sample mean and standard deviation of yield pricing errors; ρ^y denotes first order sample autocorrelation coefficient of the yield pricing errors, ρ^{xr} denotes first order sample autocorrelation coefficient of the excess return pricing errors. Sample period: 1997:03 - 2019:12.

Table 5
Fit Diagnostics of the ATSM model on daily data

	n = 36	n = 60	n = 84	n = 120
		Nominal Yield Pricing Errors		
mean	0.304	0.229	-0.248	-0.179
std	0.055	0.039	0.039	0.044
ρ^y	1.000	0.997	1.000	0.997
ρ^{xr}	0.369	0.264	0.205	0.154
		Real Yield Pricing Errors		
mean		-0.108	-0.197	0.050
std		0.161	0.131	0.124
ρ^y		0.997	1.000	0.997
ρ^{xr}		0.264	0.205	0.154

Note: Time series properties of the ATSM pricing errors implied by the daily decomposition. "Mean" and "std" refers to the sample mean and standard deviation of yield pricing errors; ρ^y denotes first order sample autocorrelation coefficient of the yield pricing errors, ρ^{xr} denotes first order sample autocorrelation coefficient of the excess return pricing errors. Sample period: 1997:03:31 - 2019:12:31.

Table 6
Reaction of credit default swaps to the Treasury supply shock

	2 years	**5 years**	**10 years**	**30 years**
Coeff.	-0.003	-0.004	-0.003	-0.003
S.E.	(0.004)	(0.003)	(0.002)	(0.002)
P-value	0.417	0.206	0.217	0.250

Note: Each column is a separate regression of credit default swaps written on 2-years, 5-years, 10-years and 30-years UK government bonds on the high-frequency supply shock, respectively. Sample period from 21-Jul-2008 to 31-Dec-2019.

Table 7
Reaction of BBB-AAA corporate bond spreads to the Treasury supply shock

	1-3 years	**3-5 years**	**5-10 years**	**15+ years**
Coeff.	1.229	-0.498	-0.239	0.011
S.E.	(1.399)	(0.412)	(0.189)	(0.149)
P-value	0.380	0.227	0.207	0.940

Note: Each column is a separate regression of UK corporate bond spreads with remaining maturities between 1-3 years, 3-5 years, 5-10 years, and 15+ years compiled by Refinitiv, on the high-frequency supply shock, respectively. Sample period from 31-Mar-2001 to 31-Dec-2019.

A.1 The ATSM of Abrahams et al. (2016)

The $K \times 1$ vector of pricing factors follow an autoregression under the physical measure ($\mathbb{P}$):

$$X_{t+1} - \mu_X = \Phi(X_t - \mu_X) + \nu_{t+1}, \qquad \nu_{t+1} \sim i.i.d.N(0_{K\times 1}, \Sigma) \tag{A.1}$$

The stochastic discount factor is written as:

$$M_{t+1} = exp\Big(-r_t - \frac{1}{2}\lambda_t'\lambda_t - \lambda_t'\Sigma^{-1/2}\nu_{t+1}\Big)$$

where r_t is the nominal short rate and λ_t is $K \times 1$ the vector of risk prices. These are related to the pricing factors as: $\lambda_t = \Sigma^{-1/2}(\lambda_0 + \lambda_1 X_t)$. The short rate follows $r_t = \delta_0 + \delta_1 X_t$. Abrahams et al. (2016) define the parameters of the pricing factor dynamics under the risk neutral measure ($\mathbb{Q}$) as:

$$\tilde{\mu} = (I_K - \Phi)\mu_X - \lambda_0$$
$$\tilde{\Phi} = \Phi - \lambda_1$$

The model assumes that bond yields are affine functions of the state variables, which are assumed to be observable. Therefore, under the pricing measure, the log price, $P_t^{(\tau)}$, of a nominal zero-coupon risk-free bond with remaining time to maturity τ follows $\log P_t^{(\tau)} = A_\tau + B_\tau' X_t$. The log price of an inflation-linked bond follows similarly $\log P_{t,R}^{(\tau)} = A_{\tau,R} + B_{\tau,R}' X_t$. The price of such a bond also satisfies:

$$\begin{aligned}\log P_{t,R}^{(\tau)} &= E_t^{\mathbb{Q}}\Big[\exp(-r_t - \cdots - r_{t+\tau-1})\frac{Q_{t+\tau}}{Q_t}\Big] \\ &= E_t^{\mathbb{Q}}\Big[\exp(-r_t - \cdots - r_{t+\tau-1} + \pi_{t+1} + \cdots + \pi_{t+\tau})\Big]\end{aligned} \tag{A.2}$$

where $E^{\mathbb{Q}}$ is the expectation operator under the risk neutral measure. Q_t is the price index at time t, and $\pi_t = \ln(Q_t/Q_{t-1})$ is the one period log inflation, related to the pricing factors as $\pi_t = \pi_0 + \pi_1' X_t$.

The system of recursive linear restrictions of the bond pricing parameters can be obtained once no-arbitrage is imposed (see Ang and Piazzesi (2003)):

$$A_\tau = A_{\tau-1} + B_{\tau-1}'\tilde{\mu} + \frac{1}{2}B_{\tau-1}'\Sigma B_{\tau-1} - \delta_0$$
$$B_\tau' = B_{\tau-1}'\tilde{\Phi} - \delta_1'$$
$$A_0 = 0, \qquad B_0 = 0_{K\times 0}$$

Risk neutral counterparts are obtained by setting the price of risk parameters λ_0 and λ_1 to zero. Then, the pricing recursion modifies to:

$$\tilde{A}_\tau = \tilde{A}_{\tau-1} + \tilde{B}_{\tau-1}'(I_K - \Phi)\mu - \delta_0$$
$$\tilde{B}_\tau' = \tilde{B}_{\tau-1}'\Phi - \delta_1'$$
$$\tilde{A}_0 = 0, \qquad \tilde{B}_0 = 0_{K\times 0}$$

The inflation-linked bond recursion can be obtained by writing Equation A.2 in terms of an inflation-linked bond purchased one period ahead. Taking logs, calculating the expectation and matching coefficients in the expression for the log bond price yields the recursion:[19]

$$
\begin{aligned}
A_{\tau,R} &= A_{\tau-1,R} + (B^{\pi}_{\tau-1,R})'\tilde{\mu} + \frac{1}{2}(B^{\pi}_{\tau-1,R})'\Sigma B^{\pi}_{\tau-1,R} - \delta_{0,R} \\
(B^{\pi}_{\tau,R})' &= (B^{\pi}_{\tau-1,R})'\tilde{\Phi} - \delta_1' \\
A_{0,R} &= 0, \qquad B_{0,R} = 0_{K\times 0}
\end{aligned}
$$

where $\delta_{0,R} = \delta_0 - \pi_0$ and $B^{\pi}_{\tau,R} = B_{\tau,R} + \pi_1$. Similar to nominal bonds, the risk neutral counterparts are given by:

$$
\begin{aligned}
\tilde{A}_{\tau,R} &= \tilde{A}_{\tau-1,R} + (\tilde{B}^{\pi}_{\tau-1,R})'(I_K - \Phi)\mu - \delta_{0,R} \\
(\tilde{B}^{\pi}_{\tau,R})' &= (\tilde{B}^{\pi}_{\tau-1,R})'\Phi - \delta_1' \\
\tilde{A}_{0,R} &= 0, \qquad \tilde{B}_{0,R} = 0_{K\times 0}
\end{aligned}
$$

where $\tilde{B}^{\pi}_{\tau,R} = \tilde{B}_{\tau,R} + \pi_1$.

The elements of yields can be obtained as the following. We use the risk adjusted counterparts of the pricing recursion coefficients $\tilde{A}_{.}$ and $\tilde{B}_{.}$ to calculate the risk adjusted fitted yields. These yields are interpreted as the time t expectation of average future short rates over the next τ periods:

$$
\frac{1}{\tau}\sum_{i=0}^{\tau} E_t r_{t+i} = -\frac{1}{\tau}\Big[\tilde{A}_\tau + \tilde{B}_\tau' X_t\Big], \qquad \frac{1}{\tau}\sum_{i=0}^{\tau} E_t r_{t+i,R} = -\frac{1}{\tau}\Big[\tilde{A}_{\tau,R} + \tilde{B}_{\tau,R}' X_t\Big]
$$

The difference between the nominal and the real expected short rates are the average expected future inflation over the next τ periods:

$$
\frac{1}{\tau}\sum_{i=0}^{\tau} E_t(\pi_{t+i}) = -\frac{1}{\tau}\Big[\tilde{A}_\tau + \tilde{B}_\tau' X_t\Big] - \left(-\frac{1}{\tau}\Big[\tilde{A}_{\tau,R} + \tilde{B}_{\tau,R}' X_t\Big]\right)
$$

Term premiums can be obtained by subtracting the expectation component from the fitted yields:

$$
TP_t^{(\tau)} = -\frac{1}{\tau}\Big[A_\tau + B_\tau' X_t\Big] - \left(-\frac{1}{\tau}\Big[\tilde{A}_\tau + \tilde{B}_\tau' X_t\Big]\right)
$$

for nominal term premium, and similarly for the real term premium $TP_{t,R}^{(\tau)}$. Inflation risk premium is obtained as the difference between the fitted breakeven inflation and the inflation expectation:

$$
IRP_t^{(\tau)} = -\frac{1}{\tau}\Big[A_\tau + B_\tau' X_t\Big] - \left(-\frac{1}{\tau}\Big[A_{\tau,R} + B_{\tau,R}' X_t\Big]\right) - \frac{1}{\tau}\sum_{i=0}^{\tau} E_t(\pi_{t+i})
$$

[19] For details see Abrahams et al. (2016)

A.2 A term structure model of nominal and real yields with supply effects

A.2.1 THE SETUP

The model is set in continuous time with two types of assets: nominal and inflation-linked (or real) zero-coupon bonds. These bonds have maturities τ in the interval $(0; T]$. An inflation-linked bond with maturity τ pays one unit of wealth at at time $t+\tau$. Its time t price is denoted by $P_t^{R,(\tau)}$. A nominal bond with maturity τ pays one unit of currency at time $t+\tau$. Its time t price is denoted by $P_t^{N,(\tau)}$. The bond's spot yields are denoted by $y_t^{R,(\tau)}$ and $y_t^{N,(\tau)}$. They are related to the prices by:

$$y_t^{N,(\tau)} = -\frac{\log P_t^{N,(\tau)}}{\tau} \tag{A.3a}$$

$$y_t^{R,(\tau)} = -\frac{\log P_t^{R,(\tau)}}{\tau} \tag{A.3b}$$

The instantaneous risk-free real rate is denoted by r_t. It is defined as $\lim_{\tau\to 0} y_t^{R,(\tau)} = r_t$ and it follows the Ornstein-Uhlenbeck process

$$dr_t = \kappa_r(\bar{r} - r_t)dt + \sigma_r dB_{r,t} \tag{A.4}$$

This rate can be interpreted as the return of a linear and instantaneously riskless production technology. Instantaneous inflation is also assumed to follow the Ornstein-Uhlenbeck process

$$d\pi_t = \kappa_\pi(\bar{\pi} - \pi_t)dt + \sigma_\pi dB_{\pi,t} \tag{A.5}$$

where $\bar{r}, \kappa_r, \sigma_r, \bar{\pi}, \kappa_\pi, \sigma_\pi > 0$ are constants and $B_{r,t}$ and $B_{\pi,t}$ are independent Brownian motions. Parameters $\bar{r}$ and $\bar{\pi}$ are the long-run means of the processes, κ_r and κ_π are the mean-reverting parameters. The volatility parameters are σ_r and σ_π.

Bonds are issued by a government and traded by arbitrageurs and other investors that are not modelled explicitly. Following Greenwood and Vayanos (2014), we treat the supply and demand of the government and other investors as price inelastic.

The amount of bonds supplied by the government, net of other investors demand, is exogenous. The supply of nominal bonds $s_t^{N,(\tau)}$ is given by a one factor model, as in Greenwood and Vayanos (2014). For simplicity, inflation-linked bond supply $s_t^{R,(\tau)}$ is fixed.

$$s_t^{N,(\tau)} = \zeta^N(\tau) + \theta^N(\tau)\beta_t \tag{A.6a}$$

$$s_t^{R,(\tau)} = \zeta^R(\tau) \tag{A.6b}$$

The functions $\zeta^N(\tau)$, $\zeta^R(\tau)$, and $\theta^N(\tau)$ are deterministic functions of the maturity of the bonds. The variable β_t is a stochastic nominal bond supply factor that follow the Ornstein-Uhlenbeck process. Its long-run mean is zero, similar to our high-frequency futures price shock series.

$$d\beta_t = -\kappa_\beta \beta_t dt + \sigma_\beta dB_{\beta,t} \tag{A.7}$$

The function $\zeta^N(\tau)$ gives the average supply of bonds at maturity τ, while $\theta^N(\tau)$ measures the sensitivity of the nominal bond supply to the supply factor β_t. We assume that $\theta^N(\tau)$ has the following properties:

Assumption 1 *The functions $\theta^N(\tau)$ satisfies*
(i) $\int_0^T \theta^N(\tau) \geq 0$;
(ii) There exists $\tau^* \in [0;T)$ such that $\theta^N(\tau) < 0$ for $\tau < \tau^*$ and $\theta^N(\tau) > 0$ for $\tau > \tau^*$

The first point of the assumption ensures that an increase in β_t does not decrease the total value of bonds supplied to arbitrageurs. The second point allows for the possibility that after an increase in β_t, the supply of some shorter maturity bonds can decrease, while the total supply of bonds does not decrease. These assumptions ensure that an increase in β_t makes arbitrageurs equilibrium portfolio more sensitive to inflation and duration risks. We assume $B_{\beta,t}$ is independent of $B_{r,t}$ and $B_{\pi,t}$. Greenwood and Vayanos (2014) considers a case where $B_{\beta,t}$ is correlated with $B_{r,t}$ which is reasonable given their empirical measure of supply. In our case, assuming independence corresponds more our high-frequency supply shock in Section 3.

A.2.2 ARBITRAGEURS

Arbitrageurs are assumed to be mean variance maximizers of their real wealth. They select their portfolio by solving:

$$\max_{\left\{x_t^{N,(\tau)}, x_t^{R,(\tau)}\right\}_{\tau\in(0,T]}} E_t[dW_t] - \frac{a}{2}V_t[dW_t] \tag{A.8}$$

W_t denotes arbitrageurs' real wealth, a is the coefficient of risk aversion. $x_t^{N,(\tau)}$ and $x_t^{R,(\tau)}$ are the units of wealth invested in the nominal bond and the inflation-linked bond with maturity of τ. Vayanos and Vila (2021) gives the interpretation for this setting that there are overlapping generation of arbitrageurs living over infinitesimal periods. A generation, born in t with wealth W_t, invests from t to $t + dt$ and then consumes and dies at $t + dt$. The corresponding budget constraint to the problem is given by:

$$dW_t = \int_0^T \left(x_t^{N,(\tau)} \frac{dP_t^{N,(\tau)}}{P_t^{N,(\tau)}} + x_t^{R,(\tau)} \frac{dP_t^{R,(\tau)}}{P_t^{R,(\tau)}} \right) d\tau - \left(\int_0^T x_t^{N,(\tau)} d\tau \right) \pi_t dt$$
$$+ \left(W_t - \int_0^T \left(x_t^{N,(\tau)} + x_t^{R,(\tau)} \right) d\tau \right) r_t dt \tag{A.9}$$

The first expression is the return from investing in bonds, as $\int_0^T x_t^{N,(\tau)} d\tau$ and $\int_0^T x_t^{R,(\tau)} d\tau$ are the amount of wealth invested in nominal bonds and inflation-linked bonds respectively. The second term $\left(\int_0^T x_t^{N,(\tau)} d\tau \right) \pi_t dt$ deflates the return from nominal bonds. Finally, the last expression is the return gained by investing the remaining wealth in the risk-free rate.

A.2.3 SOLVING THE MODEL

The model is solved by first conjecturing and later verifying that equilibrium spot rates are affine functions of the risk factors. The price of the nominal bond $P_t^{N,(\tau)}$, and the price of the inflation-linked bond $P_t^{R,(\tau)}$ are:

$$P_t^{N,(\tau)} = e^{-[A_r^N(\tau)r_t + A_\beta^N(\tau)\beta_t + A_\pi^N(\tau)\pi_t + C^N(\tau)]} \tag{A.10a}$$
$$P_t^{R,(\tau)} = e^{-[A_r^R(\tau)r_t + A_\beta^R(\tau)\beta_t + C^R(\tau)]} \tag{A.10b}$$

Lemma 1 *The dynamics of the nominal bond prices and the inflation-linked bond prices are given by*

$$\frac{dP_t^{N,(\tau)}}{P_t^{N,(\tau)}} = \mu_t^{N,(\tau)} dt - A_r^N(\tau)\sigma_r dB_{r,t} - A_\beta^N(\tau)\sigma_\beta dB_{\beta,t} - A_\pi^N(\tau)\sigma_\pi dB_{\pi,t} \tag{A.11a}$$
$$\frac{dP_t^{R,(\tau)}}{P_t^{R,(\tau)}} = \mu_t^{R,(\tau)} dt - A_r^R(\tau)\sigma_r dB_{r,t} - A_\beta^R(\tau)\sigma_\beta dB_{\beta,t} \tag{A.11b}$$

where instantaneous expected returns $\mu_t^{N,(\tau)}$ and $\mu_t^{R,(\tau)}$ are given by (B.1a) *and* (B.1b) *in Appendix B.1.*

Having derived the price dynamics of the two assets, we can substitute into the budget constraint (A.9) and solve the arbitrageurs' optimization problem (A.8). This is derived in Section B.1 in the Online Appendix.

Lemma 2 *The first order conditions are given by:*

$$\mu_t^{N,(\tau)} - \pi_t - r_t = A_r^N(\tau)\lambda_{r,t} + A_\beta^N(\tau)\lambda_{\beta,t} + A_\pi^N(\tau)\lambda_{\pi,t} \tag{A.12a}$$

$$\mu_t^{R,(\tau)} - r_t = A_r^R(\tau)\lambda_{r,t} + A_\beta^R(\tau)\lambda_{\beta,t} \tag{A.12b}$$

where coefficients $\lambda_{i,t}$ are given by:

$$\lambda_{i,t} = a\sigma_i^2 \int_0^T x_t^{N,(\tau)} A_i^N(\tau) + x_t^{R,(\tau)} A_i^R(\tau) d\tau \qquad \textit{for } i = r, \beta \tag{A.13}$$

$$\lambda_{\pi,t} = a\sigma_\pi^2 \int_0^T x_t^{N,(\tau)} A_\pi^N(\tau) d\tau \tag{A.14}$$

Equations (A.12a) and (A.12b) are also the no-arbitrage conditions in the model. No arbitrage requires the existence of prices to each risk factor. Then, the expected excess return of each asset over the short rate is equal to the asset's sensitivity to the risk factors times the risk factor's price, summed across all risk factors. The coefficients $\lambda_{i,t}$ are the prices of the risk factors, measuring the expected excess return per unit of sensitivity to each factor. They are determined through equilibrium conditions. Note, that $\lambda_{i,t}$ are proportional to how sensitive the arbitrageurs' portfolio is to factor *i*. For example, the sensitivity of the portfolio to the short rate is $\int_0^T x_t^{N,(\tau)} A_r^N(\tau) + x_t^{R,(\tau)} A_r^R(\tau) d\tau$. As inflation-linked bonds shield investors from inflation, the inflation risk factor only loads on the nominal bond. Note, that even the real return of the nominal bond is sensitive to inflation risk.

A.2.4 EQUILIBRIUM TERM STRUCTURES

In equilibrium the supplied amount of bonds will be equal to the investment of the arbitrageurs.

$$x_t^{N,(\tau)} = s_t^{N,(\tau)} \tag{A.15a}$$

$$x_t^{R,(\tau)} = s_t^{R,(\tau)} \tag{A.15b}$$

We can use the market clearing (A.15a), (A.15b), the supply (A.6a), (A.6b) and (B.1a), (B.1b) to substitute into the first order conditions (A.12a), (A.12b). This yields two functions that are affine in the risk factors r_t, β_t and π_t, verifying our initial conjecture.

Setting linear terms in r_t, β_t and π_t equal to zero gives five ordinary differential equations (ODEs) in $A_r^N(\tau)$, $A_\beta^N(\tau)$, $A_\pi^N(\tau)$, $A_r^R(\tau)$ and $A_\beta^R(\tau)$. The solutions to these ODEs are stated in Theorem 1 and derived in Section B.1 in the Online Appendix.

Theorem 1 *The nominal bond sensitivities $A_r^N(\tau)$, $A_\beta^N(\tau)$ and $A_\pi^N(\tau)$ are given by*

$$A_r^N(\tau) = \frac{1 - e^{-\kappa_r \tau}}{\kappa_r} \tag{A.16a}$$

$$A_\beta^N(\tau) = \frac{Z_r}{\kappa_r}\Big[\frac{1 - e^{-\hat{\kappa}_\beta \tau}}{\hat{\kappa}_\beta} - \frac{e^{-\hat{\kappa}_\beta \tau} - e^{-\kappa_r \tau}}{\kappa_r - \hat{\kappa}_\beta}\Big] + \frac{Z_\pi}{\kappa_\pi}\Big[\frac{1 - e^{-\hat{\kappa}_\beta \tau}}{\hat{\kappa}_\beta} - \frac{e^{-\hat{\kappa}_\beta \tau} - e^{-\kappa_\pi \tau}}{\kappa_\pi - \hat{\kappa}_\beta}\Big] \tag{A.16b}$$

$$A_\pi^N(\tau) = \frac{1 - e^{-\kappa_\pi \tau}}{\kappa_\pi} \tag{A.16c}$$

The real bond sensitivities $A_r^R(\tau)$ and $A_\beta^R(\tau)$ are given by

$$A_r^R(\tau) = \frac{1 - e^{-\kappa_r \tau}}{\kappa_r} \tag{A.17a}$$

$$A_\beta^R(\tau) = \frac{Z_r}{\kappa_r}\Big[\frac{1 - e^{-\hat{\kappa}_\beta \tau}}{\hat{\kappa}_\beta} - \frac{e^{-\hat{\kappa}_\beta \tau} - e^{-\kappa_r \tau}}{\kappa_r - \hat{\kappa}_\beta}\Big] \tag{A.17b}$$

Where Z_r, Z_π and $\hat{\kappa}_\beta$ are given by equations (B.4a), (B.4b) *and* (B.5) *respectively in Appendix B.1. The functions $C^N(\tau)$ and $C^R(\tau)$ are given in Section B.1 in the Online Appendix.*

A.2.5 ANALYSIS OF SUPPLY EFFECTS

In our empirical analysis, we found that the high-frequency supply shock raises both nominal and real yields. In the model bond yields are given by:

$$\begin{aligned} y_t^{N,(\tau)} &= \frac{1}{\tau}\left[A_r^N(\tau)r_t + A_\beta^N(\tau)\beta_t + A_\pi^N(\tau)\pi_t + C^N(\tau)\right] \\ y_t^{R,(\tau)} &= \frac{1}{\tau}\left[A_r^R(\tau)r_t + A_\beta^R(\tau)\beta_t + C^R(\tau)\right] \end{aligned}$$

Therefore, we need to show that $\partial y_t^{N,(\tau)}/\partial\beta_t = A_\beta^N(\tau)/\tau$ and $\partial y_t^{R,(\tau)}/\partial\beta_t = A_\beta^R(\tau)/\tau$ are positive.

Proposition 1 *The effect of a shock to the supply factor β_t on nominal and real yields is positive.*

Proposition 2 *The effect of a shock to the supply factor on duration and inflation risk prices is positive.*

Proposition 3 *The effect of a shock to the supply factor on yields and risk prices increases with risk aversion.*

The proofs follow from Lemma A.1. and Lemma A.2. of Greenwood and Vayanos (2014), and we present it in the Online Appendix. The intuition is the following. An increase in the supply factor increases the amount of nominal bonds held by investors in equilibrium. This increases the sensitivity of their portfolio to duration and inflation risks, raising the prices of these factors. The increase in duration risk premium and inflation risk premium raises both nominal and inflation-linked bond yields. As inflation risk loads positively only on nominal bonds, the spread between the two type of bonds widen, consistent with our empirical findings.

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