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# Monetary policy transmission during QE times: role of expectations and term premia channels

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## Abstract

This paper studies monetary policy transmission mechanisms during QE. Using high frequency yield curve event studies of monetary policy announcements in combination with a dynamic term structure model, we can identify four types of monetary policy surprises: action (working through effective policy rates), signalling (working through expected policy rates), policy uncertainty and QE-specific bond supply (both working through term premia). Applying the method to the case of the UK, we find that these channels have often operated together. Importantly, the main QE channels are transmitted to financial markets and the real economy in different ways, and only signalling is found to have ultimately affected inflation significantly.

**Key words:** Monetary policy, quantitative easing, monetary transmission mechanism, high-frequency data, dynamic term structure model, local projection model.

**JEL classification:** E43, E52, E58, G12, C58.

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# 1 Introduction

When, in the aftermath of the Global Financial Crisis of 2008, policy rates hit the zero lower bound (ZLB), major central banks launched Quantitative Easing (QE). In those days, this type of monetary policy was still classed as “unconventional” monetary policy (UMP), as it involves purchasing government bonds across a wide maturity spectrum, thereby reducing yields across the whole yield curve rather than short-term interest rates only. The lower yield curve should then feed through to lower interest rates on loans for households and businesses, thereby encouraging consumption and investment, boosting economic activity and employment and putting upward pressure on prices. That’s how QE supposed to work. And although there has been evidence for the QE-specific channels in operation affecting yield curves (see, for example, Swanson, 2021, Altavilla et al, 2019), the big open questions remain: does QE reduce yields via expected rates (“signalling channel”) or via term premia effects of asset purchases, and which type of QE channels is more efficient in stimulating the economy?

The literature seems to agree that QE helped to lower long term yields,[1] but there are inherent difficulties in evaluating transmission channels and measuring their effects beyond simple yield movements. There are two leading views of how the QE primary yield channels works. These are: the “signalling channel” working via policy rate expectations (see Bauer and Rudebusch, 2014; Bhattarai, Eggertsson, and Gafarov, 2015, for theoretical explanations and Schnabel, 2021; Haldane, 2016, for policy makers views) and the channels working through the term premia (such as “local supply”, liquidity, portfolio balance with market frictions/limits to arbitrage; see, for theory, Gertler and Karadi (2011, 2013), He and Krishnamurthy, 2013; Carlstrom, Fuerst, and Paustian (2017); Del Negro et al, 2017; Sims and Wu, 2021; Vayanos and Vila, 2021, and for

[1] See, for example, Breedon, Chadha, Waters (2012), Joyce, Lasaosa, Stevens, and Tong (2011); McLaren, Banerjee, Latto (2014), Dell’Ariccia, Rabanal, Sandri (2018) for the case of the UK literature.

policy-maker communications, Bailey, 2020; Yellen, 2011). Unfortunately, consensus on the relative importance of these channels, especially on their real-economy effects, is yet to be achieved.[2]

To a certain extent, this inconclusiveness of the existing evidence is justifiable: while short rates are under the direct control of central banks and, importantly, are directly observed, the yield curve components affected by QE, i.e. interest rate expectations and term premia, are unobserved. This implies that neither simple event studies nor traditional VAR analysis are capable of credibly identifying the channels through which QE affects the yield curve, and as a result they are not suitable for evaluating the real effects of these channels.

The contribution of our work is to identify separate channels (signalling and various channels working via term premia) from the yield curve movements and trace their real-economy effects using recent techniques. In particular, to identify the underlying shocks behind the yield curve reactions to the QE we combine the high frequency (HF) analysis of the yield curve reaction to monetary policy announcements with the dynamic term structure models (DTSM) and feed the implied yield surprise decompositions into macro models.

In a nutshell, we propose to use a term structure model to decompose high frequency yield movements around FOMC meetings into expectations shocks and various term premia shocks. The three building blocks of our approach are: 1) HF shock identification of the yield curve reaction to monetary policy announcements (to isolate monetary policy

[2]UK event studies analysing the financial market impact of QE (e.g. Joyce, Lasaosa, Stevens, and Tong, 2011; Joyce, McLaren, and Young, 2012; Christensen and Rudebusch, 2012) tend to suggest a minor role for the signalling channel and imply that the reduction in bond yields was due to a compression in term premia via local supply or the duration channel. On the other hand, the vector autogression (VAR) analysis of the macroeconomic effects of QE by Weale and Wieladek, 2016, found that QE worked by reducing uncertainty. There are more studies dedicated to the US QE effects, among which are also those suggesting a significant role for the signalling channel (as documented e.g. by Christensen and Rudebusch, 2012; Bauer and Rudebusch, 2014; Gilchrist, López-Salido, and Zakrajšek, 2015; however, these papers focused only on measuring the effects on the financial markets.)

shocks from other events and focus on the whole spectrum of maturities rather than one short term rate); 2) DTSM (to decompose the yield reaction into policy rate expectations and term premia movements); 3) Local Projection (LP) macro model to analyse the transmission of shocks identified by term premia and expectation reactions into macroeconomy.

In spirit, our approach is close to Kaminska, Mumtaz, and Sustek (2021), hereafter KMS, who identified and highlighted three instruments for US conventional monetary policy shocks representing "action", "expected path of interest rates", and "uncertainty" around it. Using local projections, they show that these three shocks can have very different impacts on macroeconomic and financial variables. This finding has an important policy implications: for the monetary policy transmission mechanism it matters not only by how much the yield curve responds to the policy, but also which component of the yield curve is driving the move. The lesson would be even more important for the subsequent period characterised by UMP, which explicitly aims to affect longer term yields via term premia (eg by affecting bond supply) and expectations channels (eg by forward guidance). To extend the analysis of Kaminska, Mumtaz, and Sustek (2021) to the period of unconventional monetary policy, the main technical issue we have to address is the presence of the ZLB, which constrains the policy rate. In particular, our term structure model used for the QE analysis cannot be affine. Hence, we base it on the shadow rate modelling approach in line with Wu and Xia (2016).

Estimating a shadow rate term structure model on the UK yields from 1997 to 2019 via Bayesian techniques and applying it to the HF yield changes around The Monetary Policy Committee (MPC) announcements, we find that both of the model implied UK longer term yield components, expectations and term premia, reacted to the monetary policy announcements, often at the same time, suggesting that transmission channels working through expectations ("signalling") and term premia often operate together.

Comparing periods of conventional and UMP, the estimated HF decomposition suggests that there was a larger role for term premium channels affecting long term yields post 2009. In fact, while the term premium was less important than expectations in driving yield reaction to MPC announcements before 2009, it is twice as reactive as policy expectations during the QE sample. The relative importance of the term premia and expectations channels varies even during the QE period: UK term premia channels were dominant during 2009-2015, whereas the "signalling" channel became more important after 2016, when the policy rate was an active tool again and the frequency of MPC meetings was decreased (i.e. changed to eight times a year instead of once a month).

Importantly, factor analysis of the decomposition across maturities shows that, to capture the term premia reaction to MPC announcements during the QE subsample, an additional factor is required (on top of the two standard term premia factors, as in KMS). The need for the QE-specific factor is consistent with the additional channels through which the QE is supposed to work. This need for a special QE factor is also consistent with the findings of Swanson (2021) for the case of US, and Altavilla et al (2019) for the Euro area, who show, albeit via different methods, that the QE-related policy surprise has been important and had persistent effects on the longer-end of the yield curve. We go further by demonstrating that this QE factor works explicitly through term premia and that it can be linked to the "supply" channel.

The two key active QE channels ("signalling" and "QE-specfic term premia") are transmitted to financial markets and then to the real economy in different ways. While the signalling channel has a pronounced and persistent impact across the whole yield curve, the effects of QE-specific term premia channel are more localised at long maturities. Furthermore, an expansionary shock depreciates the exchange rate, similar to the effects of ECB and Fed's QE estimated by Dedola et el (2021). However, we find that signalling has stronger effects on the £ real exchange rate and on financial markets than pure QE-specific term premia channel. Although both have roughly similar impacts on the real economy, only signalling generates additional inflationary pressures (consistently with the associated stronger role of the exchange rate channel). Finally, we also show that a reduction in policy rate uncertainty post 2009 has improved conditions in risky asset markets and had a significant real impact.

These findings emphasize that it is key to know the channels through which the policy works at a particular time, as the monetary transmission mechanisms and macro-impacts of QE depend on the relative importance of the channels in operation.

The remainder of the paper is organised as follows. Section 2 explains how the paper fits into the literature. Section 3 presents stylised facts about the yield curve reaction to the MPC announcements, and the DTSM and its estimation are discussed in Section 4. Estimated decompositions of the yield curve reactions to MPC announcements are analysed in Section 5. The identification of various QE surprises and their macro-economic impacts are analysed in Sections 6 and 7: Section 6 discusses the identification and the transmission mechanisms of "signalling" surprises into the real economy, while Section 7 focuses on the term premia channels. Section 8 concludes.

## 2 Related Literature

This paper contributes to several strands of the monetary economics literature.

First, our paper relates to the literature identifying monetary policy surprises from the HF reaction of the asset prices to policy announcements (Kuttner, 2001; Gertler and Karadi, 2015; Jarocinski and Karadi, 2020; Miranda-Agrippino and Ricco, 2021; and Altavilla et al, 2019, among many others). And while others usually identify the surprises of yields using information from a single asset, e.g. fed funds rate futures for the current month (like Kuttner (2001), among many others), or from a spectrum of fed funds rate futures with maturities up to a year (like, for example, Gurkaynak, Sack, Swanson, 2005), we go a step further and link high-frequency yields responses across the whole yield curve to a monthly dynamic term structure model, which mean that we can decompose the yields' responses around the MPC announcements into the changes in the expected policy rate and the changes in term premia.[3] The paper closest to ours is Kaminska, Mumtaz, Sustek (2021), who use the HF reaction of the entire US yield curve to FOMC announcements during 1997-2007 to extract three instruments to identify monetary policy surprises: action, expected path, and a surprise identified from the term premia movements - "path uncertainty". Here we provide complementary evidence by studying the UK yield curve reaction to the monetary policy announcements in the UK. In contrast to Kaminska, Mumtaz, and Sustek (2021), we expand the analysis into UMP period and uncover evidence of the additional "QE-specific" monetary policy surprise identified from the term premia reactions.

The literature that identifies QE-specific monetary policy surprises therefore constitutes the second related literature strand to which our paper is related and adds to. In particular, in line with already mentioned earlier works by Swanson (2021) and Altavilla et al (2019), we use high frequency monetary policy surprise identification combined with the factor analysis. Similarly to these earlier works, we show that, on top of "target" rate annd policy rate expectations effects, monetary policy announcements post 2008 have also affected yields through a QE-specific factor. To add to the story, here we demonstrate that this QE factor works explicitly through term premia and that it can be linked to the "supply" channel. More specifically, QE gilt purchases can affect the yield curve through the local supply channel, which arises from the scarcity that QE

[3]The idea of empirically mapping the high-frequency yield responses with the monthly term structure model to get the decomposition is not new, and have been used by others, and not only to study the monetary policy surprises. For example, Altavilla, Giannone, Modugno (2017) and Feunou, Fontaine, Roussellette (2021) study the high frequency yield responses to macroeconomic data releases, distinguishing the expectations and term premium effects, although their mapping approaches differ from ours.

creates in the purchased bonds, thereby increasing their prices or equivalently reducing their yields. For this local supply channel to operate there needs to be imperfect substitutability between different bonds.[4] As Vayanos and Vila (2021) show in a qualitative model of preferred habitat investors and arbitrageurs, local supply has effects on yields via term premia. In terms of methodology, to identify QE-specific channels, a number of papers have focused on yield reactions to policy announcements, including D'Amico et al (2012), Joyce and Tong (2012), and Altavilla et al (2021), exploiting high-frequency responses of bond yields to news about the size and maturities of bond purchases. As a result, they show that local supply channels played a role in compressing yields of eligible bonds. Our approach differs to theirs, as we identify the existence of the QE-specific surprise entirely from the term structure of the yield reactions to the announcements, without using the information on individual bond purchases (which, in fact, was not available to market participants at the time of the announcements). The reaction of policy rate expectations and term premia to MPC announcements is summarised by principal components which distil the information from movements observed across different maturities into a small set of variables. The more complex term premia reaction to MPC announcements post-2009 turns out to require an additional explanatory factor (principal component). To gain further intuition, we analyse the factor behaviour across the announcements and show that this factor is most prominent during the largest QE announcements and for longer maturities, which in turn lead us to conjecture its link to the local supply channel.

Third, we explore how QE affects financial markets and wider economy. The litera-

[4] This can arise if some investors value certain bond maturities more highly than others for reasons other than expected return or risk (possibly because they are trying to hedge certain liabilities or have regulatory constraints they have to satisfy). There is detailed evidence suggesting that ICPFs have preferred habitats in the Gilt market (Giese et al., 2021). Even if certain investors have preferred maturity habitats, yields will only be sensitive to scarcity in certain gilts if there is some market imperfection that prevents the activities of arbitrageurs offsetting the effects, eg if arbitrageurs are capital constrained or more broadly are risk averse.

ture discussed above, and in particular papers based on the event studies, seems to agree that the unconventional monetary policy is effective in lowering bond yields. There are also studies, who similarly to ours go further and use a term structure model to decompose the yield curve into the policy rate expectations and term premia and study the effects of QE on the two yield components (like Christensen and Rudebusch, 2012, Bauer and Rudebusch, 2014, Kaminska and Zinna, 2020, among others), however they do not analyse further transmission of these effects into real economy.[5] By contrast, the aim of our work is to analyse a full set of individual channels through which QE impacts interest rate expectations and term premia and to get a comparative assessment of their effects on the economy.

Although less numerous than studies of financial market effects of QE, several available studies analyse the macroeconomic impact of UK QE with the help of VAR models. But establishing effects of QE on the wider economy is less obvious, given that it takes many months for the policy to feed into macro-economic aggregates. For example, capturing the QE shock by the reduction in government bond yields, Kapetanios, Mumtaz, Stevens, and Theodoridis (2012) and Baumeister and Benati (2013), among others, show that QE stimulated the economy and had positive inflationary effects. (See Dell'Ariccia, Rabanal, Sandri (2018) for the more comprehensive review.) However, these are the aggregate effects, and such VAR models cannot identify which particular QE channel (e.g. signalling, local supply, or uncertainty) was driving the bond yield response. To the best of our knowledge, none of the previous studies explore the macroeconomic effects of the various QE channels in a consistent and systematic way. Our approach instead allows us to study and compare the effects of various QE channels ony yield curve, financial markets and the economy more widely. Moreover, the approach documented in this paper can also say whether the effects of these channels are stronger or weaker relative

[5]The analysis of term premia channels is also reduced form, while here we identify and analyse a larger spectrum of monetary policy channels affecting term premia.

to the conventional monetary policy.

# 3 Yield curve reaction to MPC announcements: pre- and post-QE

Before going into the details of our approach, here we first share some stylised facts about the yield curve reaction to MPC announcements, emphasising different patterns of responses during conventional and unconventional monetary policy periods.

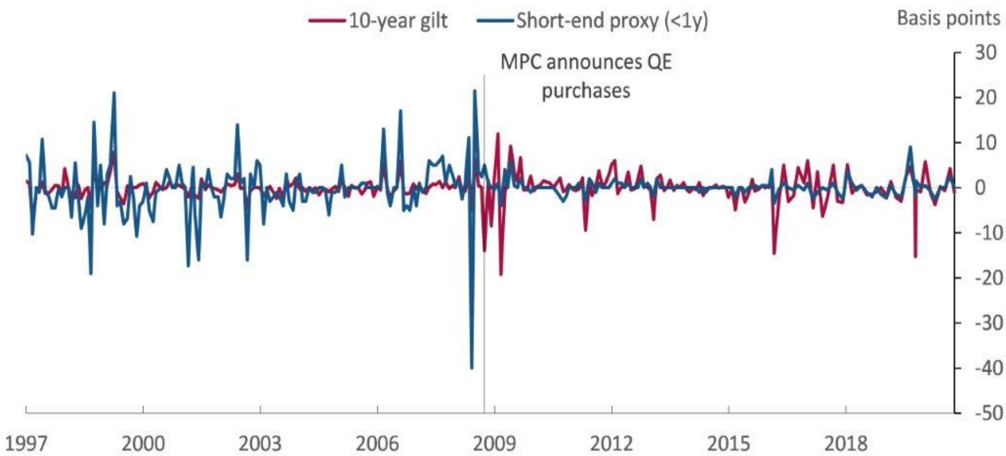
Our HF data source is Refinitiv Tick History. We use gilt yields at 1, 2, 5 and 10 year maturities. For the very front end of the yield curve (shorter than 1 year), a composite measure from the first 4 short sterling future contracts is used. Short sterling futures are exchange traded contracts linked to the 3-month LIBOR rate. They have historically been and still remain an actively traded instrument to express MPC expectations. Overall, thel yield curve up to 10 years should be well captured by the selected range of maturities.

As in some earlier literature, the changes in yields are measured in a window spanning up to 50 minutes long around the MPC announcement. Specifically, we use the difference in median yields over a 10-minute window 20 minutes before and after the event. So, for a 12pm announcement, the pre-window is 11.40 to 11.50am, and the post-window is 12.20 to 12.30pm. The approach with median yields in a pre- and post-window is taken to avoid bias from outlier values at a single point in time; outliers appeared somewhat prevalent further back in the sample at shorter maturities.

The sample period we consider consists of 252 MPC meetings from June 1997 to December 2019, with the pre- and post-QE periods roughly equally represented (133 vs 119). Regular MPC meetings occurred monthly before September 2016, and then eight times per year, with occasional special meetings during periods of macroeconomic stress.

Focusing on the UK QE transmission to yields, Figure 1 shows the striking difference between yield reactions to MPC announcements before and after 2009. While the yields at short maturities were highly reactive to MPC announcements before 2009, their response is barely noticeable in the post-2009 sub-sample. This is not entirely surprising as after 2009 Bank Rate was close to the ZLB, which for much of the period is likely to also have been the perceived ELB. As such, it left limited room for short rates to move lower, and, on the upside, hawkish monetary policy surprises were minimal. In contrast, the longer maturity yields became much more reactive to monetary policy after 2009 compared to the pre-QE period.

Figure 1: **HF yield changes around MPC announcements.**




Note: Difference in yields within a window spanning up to 50 minutes around the MPC announcements. The short rate proxy is a mix of the first four short sterling future contracts. Data source: Refinitiv Tick History.

The divide between pre- and post-QE responses across maturities shown in Figure 1 is probably better presented by Table 1, which reports the basic statistics for these series. Consistently with the case of the US yield curve (see KMS), we find that the whole UK yield curve is highly reactive to monetary policy, even over the sample of conventional monetary policy. Yet, the largest reactions in 10-year gilt yields over the sample all happened post 2009 and coincided with the MPC announcements of the increases in the stock of QE, such as during 5 March 2009 (the first official QE announcement), 6 August 2009 (announcing also an extension of the purchase range), and 4 August 2016. Two of these dates also announced Bank Rate change, and the last one also announced the launch of the Corporate Bond Purchases Scheme (CBPS), making them the richest among the announcements, potentially affecting the yield curve through the array of the channels working through rate expectations and term premia.

Interestingly, the shock volatility patterns are almost opposite between the two sub-samples. Over the sub-sample of conventional monetary policy (1997-2008), volatility was decreasing with maturity, so that the volatility of the long end of the yield curve is almost 4 times smaller than for the short end (7 vs 2). However, the pattern is the opposite for the QE period, where yield response volatility is increasing with maturity. In particular, since 2009, 10-year yield responses have been more than twice as volatile compared to 3-month rates (3.9 vs 1.5). Interestingly, compared to the pre-QE levels, the long end of the curve became twice as volatile during the QE sample (3.9 vs 2). A similar pattern can also be found in the range of yield curve reactions: since 2009, the range has shrunk materially at the shorter maturities relative to pre-2009, while widening out at the 10-year point.

The correlation pattern of the responses has also changed with the QE. As can be seen from Table 2, there is a larger disconnect between the reaction of the short and longer maturities post-QE (compare first column and first row): while the whole yield curve seemed to respond consistently to MPC announcements before 2009 (the correlation between responses across maturities are all in the range of 0.75-0.96), the reaction of the short end of the yield curve has become less correlated with medium and long maturities (0.46-0.65) since the launch of the QE.

This evidence points towards the larger role of longer term yields in the monetary policy transmission mechanism, in line with how QE is supposed to work. But has the elevated sensitivity of the longer term yields during the QE been driven by a larger role for term premia or a greater role of the channel working through the expected policy rates? In principle, this disconnect between short and longer maturity yields and the elevated volatility of the long end of the UK yield curve since 2009 could be consistent with both - the larger role for term premia in the transmission of QE (eg via the QE local supply channel) and/or a greater role for the signalling channel during the QE. To understand the channels better and to identify where the elevated volatility of the long end of the yield curve is coming from – expectations or term premia – we can employ the DTSM based approach of KMS.

# 4 Empirical Methodology

## 4.1 Model application to ZLB

As is standard in the term structure literature, assume that interest rates depend on $n$ factors. The $(n \times 1)$ vector of state variables is defined as $X_t$. We assume that the $(n \times 1)$ vector of state variables follows a first order Gaussian vector autoregressive process under the physical measure $\mathbb{P}$:

$$X_t = \mu^P + \phi^P X_{t-1} + \Sigma u_t \tag{1}$$

Further, we assume an essentially affine stochastic discount factor as in Duffee (2002):

$$M_{t+1} = exp(-r_{t+1} - 0.5\lambda_t' \lambda_t - \lambda_t \epsilon_{t+1}), \tag{2}$$

where $\lambda_t$ is the price of risk, affine in the factors that affect the term structure:

$$\lambda_t = \lambda_0 + \lambda_1 X_t, \tag{3}$$

and the short term interest rate $r_t$ also depends only on factors $X_t$. Finally, shadow rate can be expressed as

$$s_t = \delta_0 + \delta_1 X_t. \tag{4}$$

The empirical relevance of the ZLB constraint and the importance of accounting for it when carrying out inference about interest rates and monetary policy near the ZLB have been well recognised in the term structure literature. (See, for instance, Christensen and Rudebusch (2015) and Bauer and Rudebusch (2016).) This implies that the standard Gaussian Affine Term Structure Models (GATSM), which are usually employed to decompose long term rates and analyse the term premia and expected rate components, are not suitable for studying the ZLB period, as they do not impose the non-negativity restrictions. Therefore, to better understand the behaviour of UK yield curve and their components post 2009, we depart from the convenient affine representation and employ the so-called "shadow rate term structure models" (SRTSM) framework, which explicitly impose ZLB restrictions on interest rates (See, for instance, Krippner (2015), Wu and Xia (2016), Bauer and Rudebusch (2016)). In particular, the lower bound on observed short-term interest rates can be enforced by allowing the observed rate to be equal to the corresponding shadow short rate only when the latter is above the lower bound, and otherwise equal to the lower bound:

$$r_t = max(s_t; r). \tag{5}$$

Under absence of arbitrage, the price $p_{t,\tau}$ of a zero-coupon bond with $\tau$ months to maturity can be expressed as

$$p_{t,\tau} = E_t \left[ \exp\left( -\sum_{j=0}^{\tau-1} r_{t+j} \right) \right],$$

The assumption in (5) implies that yields are nonlinear in state variables and do not have an analytical expression. Denote by $f_{t,\tau}$ the time $t$ one period forward rate for a loan starting at $t+\tau$. Wu and Xia (2016) show that, under (1)-(4), the forward rate $f_{t,\tau}$ is approximately equal to:

$$f(X_t, j; \Psi) = \underline{r} + (a_{f,n} + b_{f,n}X_t - \underline{r})\phi\left(\frac{a_{f,n} + b_{f,n}X_t - \underline{r}}{\sigma_n^Q}\right) + \sigma_n^Q \phi\left(\frac{a_{f,n} + b_{f,n}X_t - \underline{r}}{\sigma_n^Q}\right) \quad (6)$$

where:

$$b_{f,n} = \delta_1' \left(\phi^Q\right)^n \quad (7)$$

$$a_{f,n} = \delta_0 + \delta_1' \left(\sum_{j=0}^{n-1} \left(\phi^Q\right)^j\right) \mu^Q - 0.5\delta_1' \left(\sum_{j=0}^{n-1} \left(\phi^Q\right)^j\right) \left(\Sigma\Sigma'\right) \left(\sum_{j=0}^{n-1} \left(\phi^Q\right)^j\right)' \delta_1 \quad (8)$$

$$\sigma_n^Q = \sum_{j=0}^{n-1} b_{f,j}' \Sigma b_{f,j} \quad (9)$$

The set of unknown parameters and states is W=$(\phi^P, \mu^P, \phi^Q, \delta_0, \Sigma, \varpi, X_t)$.

Note that $\delta_1$ is fixed to a vector of ones and $\mu^Q = 0$. Denote $\beta = vec\left(\left[\phi^P, \mu^P\right]\right)$ and $\Omega = \Sigma\Sigma'$.

## 4.2 DTSM Estimation

The described model can be represented in the state-space form, where the transition equation is given by (1) and the observation equation of the non-linear state-space model is defined as

$$y_{n,t} = \frac{1}{n}\sum_{j=0}^{n-1} f(X_t, j; \Psi) + e_{n,t}, e_{n,t} \sim N(0, \varpi) \quad (10)$$

To estimate the model we use the Bayesian methods. A Bayesian approach to estimation offers three advantages. First, the Gibbs algorithm breaks a complex problem into draws from a series of conditional posterior distributions that are more tractable. Second, imposing standard Bayesian VAR priors on the transition equation improves the precision of the estimates. Third, the Bayesian approach automatically provides error bands for all parameter estimates. In contrast, we find that estimation of this model via maximum likelihood suffers from computational problems.[6]

The prior distributions are described in the appendix. We assume a Minnesota type prior for the VAR coefficients. For the remaining parameters we use non-informative priors. The model is estimated using a Gibbs sampling algorithm. Here we provide a brief sketch of the algorithm with the details provided in the appendix. The algorithm involves sampling from the following conditional posterior distributions:

1. $H(\phi^P, \mu^P|\Psi)$. Conditional on all remaining parameters (denoted by $\Psi$), the model collapses to a Bayesian VAR and the conditional posterior of the VAR coefficients is a normal distribution.

2. $H(\phi^Q, \delta_0|\Psi)$. The observation equations constitute a set of non-linear equations which depend on $\phi^Q, \delta_0$. We use a random walk Metropolis step to draw from the conditional distribution of these parameters.

3. $H(\Sigma|\Psi)$. $\Sigma$ enters both the observation and transition equation of the state-space. Conditional on a draw for the factors and the remaining parameters, it is straightforward to draw from $H(\Sigma|\Psi)$ using a random walk Metropolis step.

4. $H(X_t|\Psi)$. We use the particle Gibbs sampler with ancestor sampling (see Andrieu, Doucet, Holenstein (2010) and Lindsten, Jordan, Schon (2014) to draw from the conditional posterior distribution of the factors $X_t$.

[6]The results from the ML estimation are highly dependent on initial values, as the likelihood appears to have many local optima.

5. $H(\varpi|\Psi)$. The conditional posterior for $\varpi$ is inverse Gamma and this parameter can be easily drawn.

The algorithm uses 500,000 total iterations with a burn-in period of 5000 and saves every 50th draw.

The model is estimated on monthly data for forward rates at maturities of 3, 6, 12, 36, 60 and 120 months, obtained from the Bank of England database. The sample runs from 1997 to 2019 to match the availability of HF data on yield curve MPC surprises described earlier.

# 5 Results

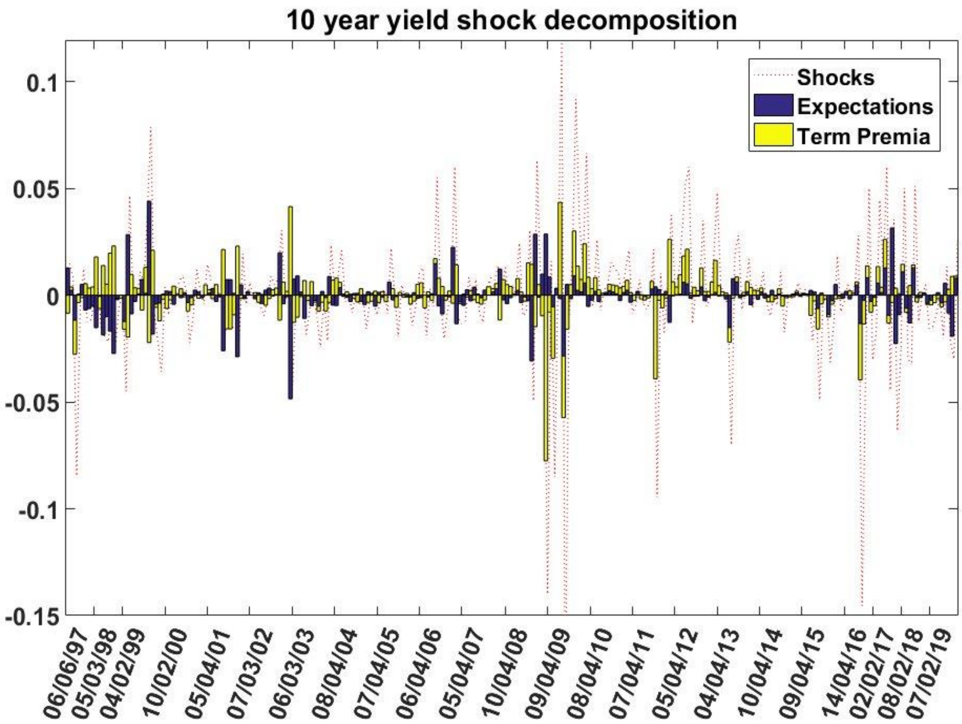
## 5.1 HF yield shock decomposition around MPC announcements

An advantage of the approach is the ability to decompose the HF surprises at a given maturity into more granular shocks. Figure 2 shows the time series of HF 10-year yield shocks, as well as the model implied decomposition of the surprise into the expectations and term premia. Evidently, both components reacted to monetary policy announcements, often at the same time, suggesting that transmission channels working through expectations and term premia have often operated together. The channel working through expectations has been important throughout the whole sample: the volatility of expectations around MPC announcements is roughly the same on pre and post-QE sub-samples.[7] The largest reactions in expectations coincide with the November 2008, March 2009, and November 2017 announcements, each of which involved changes in Bank Rate (and on top of that, in March 2009, the first QE programme was announced),

[7]The decomposition shown here is for our baseline unrestricted model. We also tried bias-adjusted version of the model with zero restrictions imposed on some prices of risk parameters and the decompositions turn out to be qualitatively robust, showing only small quantitative differences.

leading to significant revisions to market perceptions of its future path.

Figure 2: **Model implied 10-year yield shock decomposition around MPC announcements.**




Note: The shock is estimated as a difference in yields within a window spanning up to 50 minutes around the MPC announcements. The model implied decomposition into the expectations and term premia is based on Wu and Xia (2016) model estimated on the sample of UK monthly forward rate data from 1997 to 2019.

Table 3 documents the sensitivity of term premia and expectations components to MPC announcements during periods of conventional and UMPs across the spectrum of maturities. The expectations component has become less important at shorter maturities. The reduced role of policy rates due to the ZLB proximity and, as a consequence, the reduced role of the path of monetary policy rates, could be a possible factor affecting the volatility of the expectations component, especially at shorter horizons. And to the extent that term premia partially reflect lower uncertainty about short-term interest rates resulting from UMPs, like forward guidance and QE (see e.g. Kaminska and Roberts-Sklar (2018)), it is unsurprising that premia at shorter horizons have also became less volatile.

However, the picture is different for longer maturities. Comparing periods of conventional and unconventional monetary policies, the HF decomposition suggests that term premia channels had a larger role in explaining 10-year yields post 2009. In fact, while the term premium was less important than expectations in driving yield reactions to MPC announcements before 2009, premia reacted almost twice as much as policy expectations during the QE sample. Given that QE purchases were focused on longer maturities, this elevated role of term premia at the longer horizons is thus consistent with larger role of the supply channel, which could have dominating and offsetting effects on longer term yields with respect to lower uncertainty about monetary policy rate path. Interestingly, the relative importance of the term premia and expectations channels is not constant and varies even within the QE sub-sample, e.g. in case of 10-year yields, UK term premia channels were dominant during 2009-2015, while expectations – during 2016-2019. The results are therefore consistent with findings based on the earlier UK QE rounds, e.g. of Christensen and Rudebusch (2012) or Joyce, McLaren, Young (2012), who found a weaker role for signalling than term premia channels during QE1-QE2.

## 5.2 Factor analysis of the shock decomposition pre- and post-QE.

Table 4 presents PCA analysis of the monetary policy shocks in yield components. And again, we find interesting differences between conventional and unconventional monetary policy periods. In particular, over the period preceding the GFC, the analysis suggests that two factors were needed to explain the reaction in expectations component of the yields (explaining 99 percent of the variation) and two factors to capture the movements in term premia across maturities (explaining 94 percent of the variation). This is similar to the results obtained by KMS for the US shocks estimated on the pre-GFC sample.

Instead, during the UMP subsample there is a clear evidence that an additional factor is required to capture the reaction of term premia to MPC announcements (on top of the two standard term premia factors), as the first two term premia PCs explain only 89 percent of term premia variation across maturities, while, with the third PC added, that increases up to 98 percent. The need for the QE-specific factor is consistent with the additional channels through which the QE is supposed to work. This need for a special QE factor is also consistent with the findings of Swanson (2021) for the case of US, and Altavilla et al (2019) for the Euro area, who show, albeit via different methods, that the QE-related policy factor has been important and had persistent effects on the longer end of the yield curve. To add to their story, we find that this QE factor shows up explicitly through term premia.

To obtain the monetary policy instruments from these PCs of expectations and term premia surprises, we then follow the approach by KMS and select the most important PCs for each of the components.

In particular, based on the PCA analysis, we extract two orthogonal instruments from the expectations part of the yield curve reaction and rotate them so that the expected path component is restricted not to affect the current short rate. (The rotation is based on Gurkaynak et al (2005) and KMS). One concern with proceeding in the same way with extracting instruments from the term premia components as from the expectations might be that our term premia reactions are driven by the same factors and hence correlated with expectations, which would preclude us from identifying independent shocks from these. To address this concern, we follow KMS in first orthogonalising term premia with respect to the selected PCs of expectations, so that we work only with movements of term premia that are orthogonal to the PCs of expectations. We then carry out a PC decomposition of the part of term premia that is orthogonal to the PCs of expectations. Finally, to proceed with the factor interpretation, we apply identification strategy followed by Swanson (2021), rotating the three term premia factors under the assumption that the additional QE term premia factor has minimum variance during the pre-QE period. (The factors are calculated by an iterative procedure. Starting from an initial estimate of the term premia factors, expectations are orthogonalised. Then the expectations factors are calculated and rotated. Using these, term-premia are orthogonalised and the term premia factors are updated. This iteration is repeated until the change in the factors across iterations is below $10^{-}6$.)

Table 5 reports the loadings of the five maturities in the HF dataset on the selected instruments. Inspecting the loadings of the first two expectations factors, we notice the similarity with the action and expectations path factors identified in the earlier literature (Kaminska, Mumtaz, and Sustek (2021), Gürkaynak, Sack, and Swanson (2005)). In particular, the action factor has largest loadings on the shorter rate maturity, with its importance decreasing with maturity. And the second expectations factor exploits more the information at longer maturities having zero loadings for very short maturities, suggesting it is more related to the "expected path" of future policy rates inferred from the MPC announcements (which can contain both explicit and implicit signals about the future short-rate path (Woodford, 2003, 2012)). And although this channel was active even before the QE era, it came into focus during the QE period, when policy rates were close to ZLB, and investors interpreted asset purchase announcements as implying a lower path for future short-term interest rates. This channel was widely labeled as the "signalling channel" of QE policy transmission. We adopt this label here as well, although we extend it to the pre-QE period and use it to cover everything that moves the market expectations of the future path of the policy rate on the MPC announcements.

# 6 UMP channel working through expectations

This section further discusses the interpretation of the identified “signalling” monetary policy surprise and analyses its transmission into the real economy via the local projection model.

Figure 3 shows times series for the two expectations surprises. The action factor responded far more during the conventional monetary policy, when the policy rate was the active instrument, and became almost invisible post 2009, when policy rates stayed at the effective lower bound and UK monetary policy was operating through different tools. In relative terms, the action surprises were slightly more important than signalling before QE; during the QE period signalling surprises account for the bulk of the variation, with the action surprises contributing relatively little.

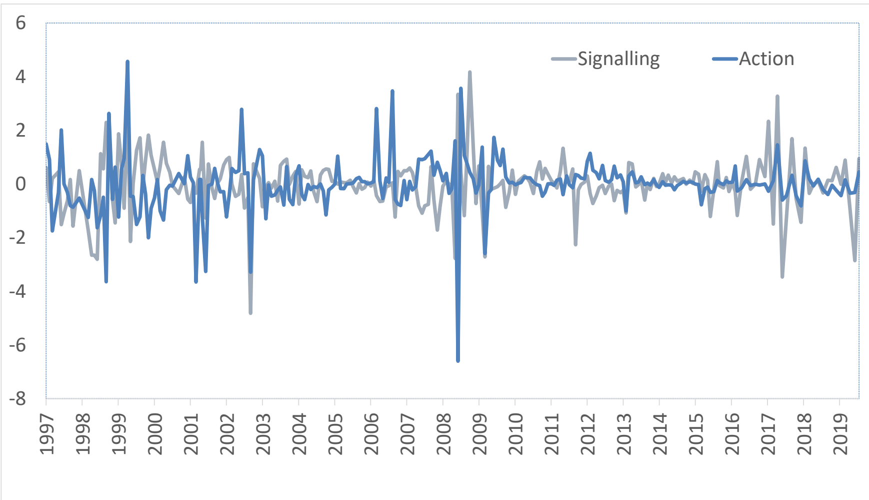
The “signalling” factor instead was quite active across the entire sample, with similar volatility levels surrounding MPC announcements before and after QE, suggesting a close relation between the signalling chanel and other communication strategies that influence market expectations of future policy rates (e.g. forward guidance). Interestingly, there is a substantial increase in signalling factor responsiveness to the MPC announcements after 2016.

We examine the effects of the ”signalling” policy changes on financial markets and macroeconomic variables of interest [8] via Bayesian local projections (LP), introduced by Miranda-Agrippino and Ricco (2015), and applied to the case of FOMC surprises during the conventional monetary policy period by Kaminska, Mumtaz, and Sustek (2021).

The LP model is estimated on monthly UK data, with LP responses estimated on the QE sub-sample only (2009-2019). The benchmark model has the following variables: unemployment, the RPI inflation rate, the IG corporate bond yield, the real exchange rate, the UK equity index FTSE, 1-year gilt yield, 10-year gilt yield and its expectations

[8] The data come from either FRED or Global Financial Data.

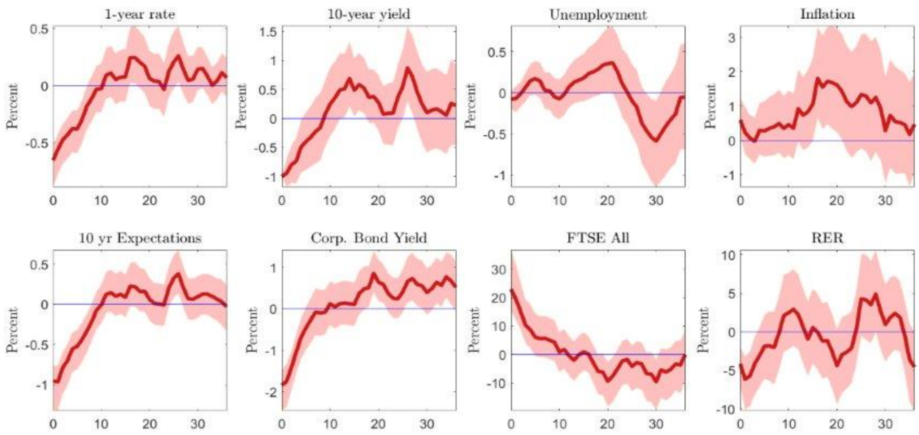
Figure 3: **Expectations instruments around MPC announcements.**




Note: The two orthogonal instruments are given by PCs from the expectations part of the yield curve reaction, rotated so that the expected path ('signalling') component is restricted not to affect the current short rate.

component. Twelve lags are used as controls. Consistently with our QE focus, the impulse responses shown in Figure 4 correspond to monetary policy easing shocks, i.e. the monetary policy surprises are normalised to decrease interest rates.

Figure 4: **Local projections: Signalling.**




Note: The horizon for the responses is 36 months. The shock is normalised to decrease the 10-year yield by 100 basis points. The charts plot the median response and the 90 percent error band. The responses are estimated over the QE sub-sample (2009-2019).

The responses to the shock identified by the "signalling channel" instrument are reported by Figure 4. It can be seen that the signal of keeping policy rates low has a material positive effect on both inflation and real activity (unemployment is significantly decreased around the 2-year policy horizon). As expected, when the policy easing is implemented through the signalling channel, the whole yield curve shifts down, with the effects driven by interest rate expectations (term premia are not affected). The impact on risky asset prices is also positive: corporate bond yields and spreads decrease and equity prices increase. The exchange rate depreciates on the impact. This finding is consistent with the FX channel of UMP, and in line with the earlier findings in the literature (see, for example, Neely (2015) and Swanson (2021) for the US case, who show that the Fed's unconventional monetary policy was associated with a large depreciation of the U.S. dollar).

# 7 UMP channels working through term premia: QE-specific and Policy Uncertainty.

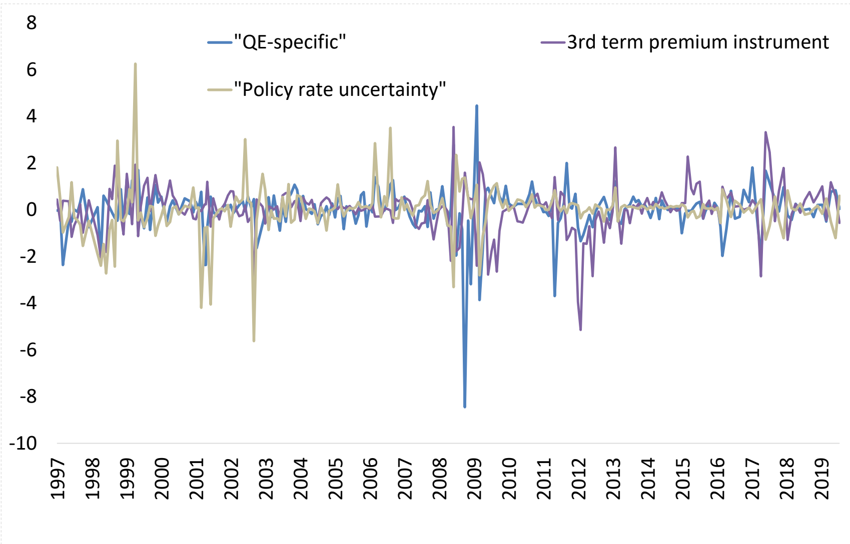
In this section we study the term premia specific channels that were in operation during QE period. We then compare and contrast their transmission mechanisms with the transmission of "signalling" monetary policy surprises.

## 7.1 The role of QE-specific policy.

Turning to term premia factors, we observe (see Figure 5) that the largest moves of the QE-specific factor, which had a minimum variance before 2009, coincided with 5 March 2009, 7 May 2009, 9 July 2009, 6 August 2009, 6 October 2011 MPC announcements, each of which was heavily loaded with the information about the QE purchases. These announcements came as large surprises to market participants, probably largest across the sample considered (according to Reuters survey of QE expectations). Hence the QE-specific term premium factor can potentially be linked to the portfolio rebalancing channel, as forward looking investors react to news of future asset purchases by asking for lower term premia on long-term bonds immediately (via so-called ex ante local supply and duration channels). To corroborate, the factor loadings are largest at medium and long term maturities, coinciding with the segment where the QE purchases were focused (the Bank of England purchased gilts with remaining maturities longer than 3 years) and where duration risk premia are largest, while loadings at very short maturities are basically zero.

To understand if these term premia factors could be used as instruments for policy surprises, we use reliability statistics by Mertens and Ravn (2013). The statistics for

Figure 5: **Term Premia instruments around MPC announcements.**

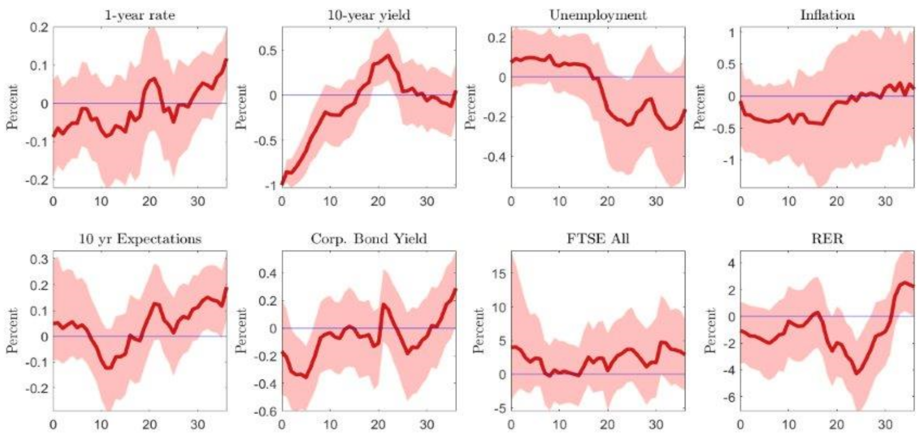



Note: The instruments are given by PCs of the estimated term premia reactions orthogonalised with respect to the selected PCs of expectations.

the QE-specific term premia is estimated to be around 0.1. This estimate is close to the values obtained by Caldara and Herbst (2018) for high frequency instruments for US monetary policy.

Figure 6 contains responses to a shock identified by the QE-specific term premia instrument, which is linked to gilt supply. As in the case of the signalling channel, easing through the term premia has a positive impact on real activity (although the pass-through to unemployment is slower, with a significant impact after around 2 years). The inflation effects, however, are insignificant. The yield curve inverts, as the negative yield impact is stronger at the longer end of the yield curve than at 1-year maturity. And while riskier asset prices increase and corporate yields are down, the impact on the exchange rate is negative, albeit small and mostly insignificant on the impact.

Figure 6: **Local projections: QE-specific.**




Note: The horizon for the responses is 36 months. The shock is normalised to decrease the 10-year yield by 100 basis points. The charts plot the median response and the 90 percent error band. The responses are estimated over the QE sub-sample (2009-2019).

To sum up, the two main channels during QE ("signalling" and "QE-specfic term premia") are transmitted to financial markets and then to the real economy in different ways. First, while the signalling channel has a pronounced and persistent impact across the whole yield curve, the effects of QE-specific term premia channel are more localised at long maturities. Furthermore, an expansionary shock depreciates exchange rates, via both signalling and QE-specific term premia channels (similar to the effects of ECB and Fed's QE estimated by Dedola, Georgiadis, Grab, Mehl (2021)); however, we find that signalling has stronger effects on the £ real exchange rate. Similarly, the signalling channel delivers a stronger boost to equity prices than pure QE-specific term premia channel. Finally, their macro impacts also differ. Although both have roughly similar impacts on the real economy, significantly easing unemployment around approximately 2 years, their inflationary impacts are different. In particular, only signalling generates inflationary pressures, consistent with the associated stronger role of the FX channel and compression of interest rates across a wider range of maturities.

## 7.2 The role of policy uncertainty.

Finally, we analyse the role of the second term premia surprise, which was also active during conventional monetary policy period prior 2009. The Mertens and Ravn reliability statistics for the policy rate uncertainty factors is estimated to be around 0.1, suggesting it is informative about policy shocks during our sample period. [9]

It turns out this term premia surprise is positively correlated with monetary policy rate uncertainty measures (eg measured by 1-year interest rate implied volatility). The measures were relatively high during the conventional monetary policy and low during QE due to the policy rate proximity to the ZLB. Consistently with the path uncertainty factor identified by KMS, this suggests that this term premium factor could be linked it to monetary policy rate uncertainty. The analysis of the time series of this term premia surprise further corroborates this interpretation. Indeed, the largest negative moves in this term premia surprise during QE subsample coincide with the announcements on

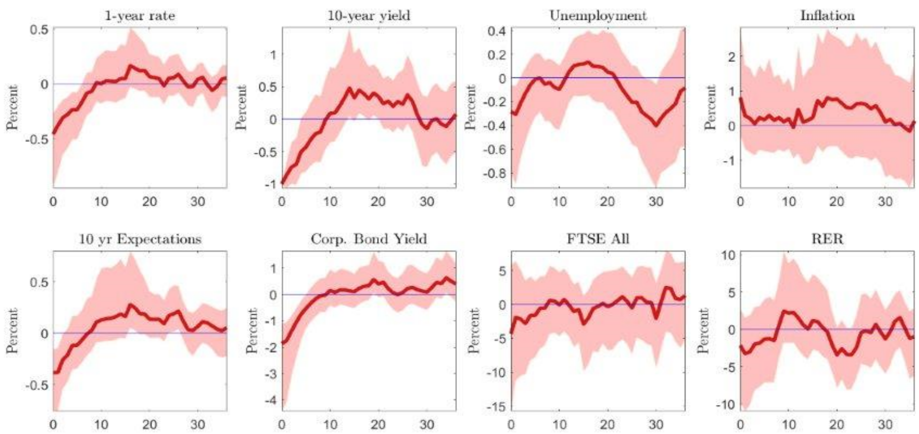
[9] In contrast, the reliability of the third term premium factor as an instrument is only around 0.03. This suggests that this factor is not informative about policy shocks over our sample period.

September 2009, August 2013, July 2016, and September 2017. Of particular interest is the 7th August 2013 announcement, when MPC introduced "forward guidance", setting out the conditions that would need to be met for the interest rate to be increased from the effective lower bound, which was intended to "provide certainty" that interest rates would not increase too soon. Lower uncertainty about future policy rates transmits to the financial markets by reducing risk premia. Consistent with this surprise interpretation, the premia that markets demand for policy rate uncertainty dropped on the announcement.

Relative to the vast literature showing that fluctuations in uncertainty have real economic effects (as, for example, Bloom (2009), Baker, Bloom, and Davis (2016), and Bianchi, Kung, and Tirskikh (2018)), the literature on the effects of uncertainty specific to the monetary policy is relatively scarce. The most prominent studies of monetary policy uncertainty are Baker, Bloom, and Davis (2016) and Husted, Rogers, and Sun (2020), which focus on the case of US monetary policy and construct the uncertainty indices using a text-based approach. Similarly to what other studies find for the effects of general economic uncertainty, Husted, Rogers, and Sun (2020) find that, in response to higher monetary policy uncertainty, borrowing costs rise and real activity declines. Different shock identifications, however, deliver different predictions as to whether higher policy uncertainty leads to higher or lower inflation.

Based on the US evidence, we could also expect the UK monetary policy rate uncertainty to have real effects. To help us understand how the macroeconomic and financial conditions actually respond to the UK policy rate uncertainty in practice, Figure 7 plots the responses of macro-financial variables to the monetary policy easing shock identified via the policy rate uncertainty factor. The policy rate uncertainty presents a useful instrument for identifying a monetary policy shock that transmits to the broader macroeconomy by reducing term premia in government and corporate bond yields, delivering a persistent boost to real activity by lowering unemployment (similar to what Husted, Rogers, and Sun (2020) find for the US case). In other words, the higher monetary policy uncertainty shock propagates into financial markets by rising corporate bond spreads, consistently with the larger impact of risk premia. Therefore, even if the UK monetary policy rate uncertainty surprises were not large post-2009, the minimal volatility of this type of monetary policy surprise during QE has also important policy implications, as it suggests that the record low policy rate uncertainty post 2009 has contributed to improved conditions in riskier asset markets (as in Kaminska and Roberts-Sklar (2018)) and in economic conditions more generally (as in Husted, Rogers, and Sun (2020)).

Figure 7: **Local projections: policy rate path uncertainty.**




Note: The horizon for the responses is 36 months. The shock is normalised to decrease the 10-year yield by 100 basis points. The charts plot the median response and the 90 percent error band. The responses are estimated over the QE subsample (2009-2019).

## 8 Conclusions

The new analysis presented here helps improve our understanding of the effects of UK unconventional monetary policy on the yield curve by separating out distinct channels (those working through policy rate expectations or term premia) and providing ways of analysing them further, including in terms of their impact on macroeconomy.

We find that asset purchases have a more important impact on term premia than conventional interest rate policy, and evidence points to significant role for a QE specific supply factor working through term premia. In particular, we show that during QE times, monetary policy affected the yield curve through signalling, policy rate uncertainty and QE-specific supply channels, all of which have important albeit distinct roles in monetary polciy transmission mechanism.

Signalling can have a particularly potent impact on financial conditions because it can have an immediate and persistent impact on interest rates across the whole of the yield curve, and so it can affect the pricing of a larger range of loans and financial assets. In contrast QE local supply effects have a more localised impact on the yield curve, concentrated mostly on the segments at the longer end of the curve. Therefore these two channels also transmit differently to the real economy. In line with this, the evidence suggests that if driven by signalling rather than term premia effects, a given reduction in long yields is associated with a relatively larger effect on the exchange rate, corporate bond yields, inflation and real activity. In addition to these affects, UMP can also compress term premia by helping to reduce monetary policy rate path uncertainty. This effect might be particularly potent when policy rates are 'stuck' close to zero and QE is paired with forward guidance. In line with this, the evidence suggests that relative to the pre-GFC period, uncertainty about the future path for Bank Rate was significantly lower after 2008; as expected this appears to translate into both lower term premia and corporate bond spreads and improved real economic outcomes.

Our results have important policy implications. We show that, although knowing the size of the yield curve reaction is important, it is also vital to know the channels through which the QE policy works at a given time, as the monetary transmission mechanisms and macro-impacts of QE may be very different contingent on the relative importance of various channels. Understanding the relative strength of different transmission channels may ultimately matter more to policy makers than whether the reaction of yields is greater or smaller at a certain point in time.

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Table 1: **Effect of MPC announcements on yields across maturities, pre- vs post-QE**

| | 3-month | 1-year | 2-year | 5-year | 10-year |
|---|---|---|---|---|---|
| 1997-2008 | | | | | |
| Average, bps | -0.4 | -0.4 | -0.5 | -0.2 | -0.0 |
| St. Deviation | 7.0 | 5.2 | 4.5 | 3.3 | 2.0 |
| Min, bps | -40 | -19 | -22 | -12 | -8 |
| Max, bps | 22 | 23 | 21 | 15 | 8 |
| 2009-2019 | | | | | |
| Average, bps | 0.1 | 0.2 | 0.0 | -0.1 | -0.1 |
| St. Deviation | 1.5 | 2.9 | 2.9 | 3.7 | 3.9 |
| Min, bps | -4 | -17 | -14 | -20 | -19 |
| Max, bps | 9 | 11 | 7 | 11 | 12 |

Note: The sample is from June 1997 to December 2019.

Table 2: **Correlations between yield responses across maturities**

| Pre-QE/ **Post-QE** | | | | | |
|---|---|---|---|---|---|
| | 3-month | 1-year | 2-year | 5-year | 10-year |
| 3-month | 1 | 0.89 | 0.85 | 0.86 | 0.75 |
| 1-year | **0.59** | 1 | 0.96 | 0.91 | 0.8 |
| 2-year | **0.65** | **0.92** | 1 | 0.94 | 0.82 |
| 5-year | **0.55** | **0.90** | **0.90** | 1 | 0.9 |
| 10-year | **0.46** | **0.82** | **0.79** | **0.95** | 1 |

Note: The pre-QE estimates are based on the sample from June 1997 to December 2008, post-QE estimates (in bold) are based on the sample from January 2009 to December 2019.

Table 3: **Volatility of yield components (term premia and expectations) on MPC announcements across maturities, pre- vs post-QE**

| | 3-month | 1-year | 2-year | 5-year | 10-year |
|---|---|---|---|---|---|
| 1997-2008 | | | | | |
| Expectations | 0.024 | 0.037 | 0.036 | 0.020 | 0.010 |
| Term premia | 0.004 | 0.003 | 0.009 | 0.012 | 0.008 |
| 2009-2019 | | | | | |
| Expectations | 0.008 | 0.019 | 0.020 | 0.012 | 0.007 |
| Term premia | 0.002 | 0.004 | 0.007 | 0.006 | 0.012 |

Note: The pre-QE estimates are based on the sample from June 1997 to December 2008, post-QE estimates are based on the sample from January 2009 to December 2019.

Table 4: **PCA of yield component responses across maturities: cumulative variance explained, pre- vs post-QE**

| | Expectations | | Term Premia | |
|---|---|---|---|---|
| | pre-2009 | post-2009 | pre-2009 | post-2009 |
| PC1 | 94.85 | 89.75 | 78.99 | 52.66 |
| PC2 | 99.18 | 97.42 | 94.35 | 89.42 |
| PC3 | 100.00 | 99.83 | 99.92 | 98.21 |
| PC4 | 100.00 | 99.98 | 100.00 | 99.75 |
| PC5 | 100 | 100 | 100 | 100 |

Note: The pre-QE estimates are based on the sample from June 1997 to December 2008, post-QE estimates are based on the sample from January 2009 to December 2019.

Table 5: **Loadings on the components of monetary policy surprises**

| | 3-month | 1-year | 2-year | 5-year | 10-year |
|---|---|---|---|---|---|
| Rotated PCs | | | | | |
| **Expectations** | | | | | |
| PC1, "Action" | 0.98 | 0.97 | 0.94 | 0.88 | 0.76 |
| PC2, "Signalling" | 0.00 | 0.20 | 0.29 | 0.47 | 0.63 |
| **Term premium** | | | | | |
| PC3, Path uncertainty | 0.98 | 0.52 | 0.39 | -0.48 | -0.11 |
| PC4, QE-specific | 0.00 | -0.03 | 0.21 | 0.86 | 0.92 |
| PC5, "residual" | 0.00 | 0.82 | 0.87 | -0.06 | -0.34 |

Note: The two PCs from the expectations part of the yield curve reaction are rotated so that the expected path ('signalling') component is restricted not to affect the current short rate. The term premium PCs are estimated from the term premia reactions, which are orthogonal to the PCs of expectations.

**APPENDIX**

**Details of MCMC estimation.**

To start with, we specify the following priors.

1. $P(\beta)$ is normal $N(\beta_0, V_0)$, $\beta_0 = 0$ and $V_0$ is a diagonal matrix with diagonal elements set to 10,000.

2. $P(\varpi)\tilde{\ }IG(T_0, D_0)$ where $T_0 = 0$ and $D_0 = 0$.

3. $P(b)\tilde{\ }N(b_0, v_0)$ where $b = \begin{pmatrix} \phi^Q \\ \delta_0 \end{pmatrix}$ with $b_0$ set equal to the maximum likelihood estimate and $v_0$ a diagonal matrix with 100 on the main diagonal. We use the Extended Kalman filter (EKF) to obtain the maximum likelihood estimates and their variance. The EKF estimate of $X_t$ is used to initialise the draw of the factors.

No prior information is assumed for any remaining parameters.

In each iteration of the algorithm, draws are made from the following conditional posterior distributions:

1. $H(\beta|b, \Sigma, \varpi, X_t)$. Conditional on $b, \Sigma, \varpi, X_t$, the model is a BVAR

$$X_t = \mu^P + \phi^P X_{t-1} + \tilde{u}_t, \tilde{u}_t \tilde{\ } N(0, \Omega) \tag{a1}$$

With a normal prior, the conditional posterior is also noromal: $N(M, V)$. The mean and variance of the conditional posterior distribution are:

$$V = \left(V_0^{-1} + \left(\Sigma\Sigma'\right)^{-1} \otimes x'x\right)^{-1}$$
$$M = V\left(V_0^{-1}\beta_0 + \left(\left(\Sigma\Sigma'\right)^{-1} \otimes x'x\right)\beta_{ols}\right)$$

where $x$ denotes the regressors in equation (a1).

2. $H(b|\beta, \Sigma, \varpi, X_t)$. Conditional on $\beta, \Sigma, \varpi, X_t$, the model is a non-linear system of $J$ equations given by $\begin{pmatrix} y_{1,t} = f(X_t, j; \Psi) + e_{1,t} \\ . \\ . \\ y_{J,t} = \frac{1}{J}\sum_{j=0}^{J-1} f(X_t, j; \Psi) + e_{J,t} \end{pmatrix}$. As shown by equations (6) to (9), $f(X_t, j; \Psi)$ is a function of $b$. We use a random walk Metropolis algorithm to draw $b$. The candidate density is defined as:

$$b_{new}\tilde{\ }N(b_{old}, c\Psi_b) \tag{11}$$

where $b_{new}$ $(b_{old})$ denotes the new (old) draw. The variance $\Psi_b$ is obtained from an initial maximum likelihood estimation of the model with the scaling factor $c$ chosen to achieve an acceptance rate between 20 and 40 percent. Draws are accepted with the probability:

$$\alpha = \min\left(\frac{f\left(y_{n,t}|b_{new},\beta,\Sigma,\varpi,X_t\right)\times P\left(b_{new}\right)}{f\left(y_{n,t}|b_{old},\beta,\Sigma,\varpi,X_t\right)\times P\left(b_{old}\right)},1\right) \tag{12}$$

where $f\left(y_{n,t}|b_{new},\beta,\Sigma,\varpi,X_t\right)$ is the likelihood function. In logs this given by $\left(\frac{T}{2}\right)\log\left|\tilde{\varpi}^{-1}\right| - 0.5\sum_{t=1}^{T}\left[E_t'\tilde{\varpi}^{-1}E_t\right]$ where $E_t = [e_{1,t},..,e_{J,t}]$ and $\tilde{\varpi}$ is a $J\times J$ diagonal matrix with $\varpi$ on the main diagonal.

3. $H\left(\Sigma|b,\beta,\varpi,X_t\right)$. Conditional on $\beta, b, \varpi, X_t$, the model is a non-linear system of $J+N$ equations given by $\begin{pmatrix} y_{1,t} = f(X_t,j;\Psi) + e_{1,t} \\ . \\ . \\ y_{J,t} = \frac{1}{J}\sum_{j=0}^{J-1} f(X_t,j;\Psi) + e_{J,t} \\ X_t = \mu^P + \phi^P X_{t-1} + \tilde{u}_t \end{pmatrix}$. As shown by equations 6 to 9, $f(X_t,j;\Psi)$ is a function of $\Sigma$ and $var\left(\tilde{u}_t\right) = \Omega = \Sigma\Sigma'$. We use a random walk Metropolis algorithm to draw $\Sigma$. Let $\tilde{\Sigma}$ denote the vectorised free elements of $\Sigma$. The candidate density is:

$$\tilde{\Sigma}_{new}\,\tilde{}\,N(\tilde{\Sigma}_{new}, d\Psi_{\tilde{\Sigma}})$$

where $d$ is a scaling factor and $\Psi_{\tilde{\Sigma}}$ is the maximum likelihood estimate of the variance of $\tilde{\Sigma}$. The acceptance probability is defined as:

$$\alpha = \min\left(\frac{f\left(y_{n,t}|\tilde{\Sigma}_{new},b,\beta,\varpi,X_t\right)}{f\left(y_{n,t}|\tilde{\Sigma}_{new},b,\beta,\varpi,X_t\right)},1\right) \tag{13}$$

where $f\left(y_{n,t}|\tilde{\Sigma}_{new},b,\beta,\varpi,X_t\right)$ is the likelihood function. In logs this given by $\left(\frac{T}{2}\right)\log\left|\tilde{\Omega}^{-1}\right| - 0.5\sum_{t=1}^{T}\left[V_t'\tilde{\Omega}^{-1}V_t\right]$ where $V_t = [e_{1,t},..,e_{J,t},\tilde{u}_t]$ and $\tilde{\Omega} = \begin{pmatrix} \tilde{\varpi} & 0 \\ 0 & \Omega \end{pmatrix}$.

4. $H\left(\varpi|\Sigma,b,\beta,X_t\right)$. Conditional on the remaing parameters, the model is a non-

linear system of $J$ equations given by $\begin{pmatrix} y_{1,t} = f(X_t, j; \Psi) + e_{1,t} \\ . \\ . \\ y_{J,t} = \frac{1}{J}\sum_{j=0}^{J-1} f(X_t, j; \Psi) + e_{J,t} \end{pmatrix}$ where $var(e_{i,t}) = \varpi$. Given an Inverse Gamma (IG) prior for $\varpi$, the conditional posterior is also IG with scale parameter $\tilde{e}_t'\tilde{e}_t + \sigma_0^2$ and degrees of freedom $T(J) + T_0$ where $\tilde{e}_t = vec(E_t)$ with where $E_t = [e_{1,t}, .., e_{J,t}]$ and $\sigma_0^2$ and $T_0$ are the prior scale parameter and degrees of freedom, respectively.

5. $H(X_t|\varpi, \Sigma, b, \beta)$. Conditional on the parameters, the non-linear state-space model is given by:

$$Y_t = F(X_t, j; \Psi) + E_t$$

$$X_t = \mu^P + \phi^P X_{t-1} + \tilde{u}_t$$

where $Y_t = [y_{1,t}, .., y_{J,t}]$, $F(X_t, j; \Psi) = \left[f(X_t, j; \Psi), .., \frac{1}{J}\sum_{j=0}^{J-1} f(X_t, j; \Psi)\right]$ and $cov(\tilde{u}_t) = \Sigma\Sigma' = \Omega, cov(E_t) = \tilde{\varpi}$. Following recent developments in the seminal paper by Andrieu, Doucet, Holenstein (2010), we employ a particle Gibbs step to sample from the conditional posterior of $X_t$. Andrieu, Doucet, Holenstein (2010) show how a version of the particle filter, conditioned on a fixed trajectory for one of the particles can be used to produce draws that result in a Markov Kernel with a target distribution that is invariant. However, the usual problem of path degeneracy in the particle filter can result in poor mixing in the original version of particle Gibbs. Recent development, however, suggest that small modifications of this algorithm can largely alleviate this problem. In particular, Lindsten, Jordan, Schon (2014) propose the addition of a step that involves sampling the 'ancestors' or indices associated with the particle that is being conditioned on. They show that this results in a substantial improvement in the mixing of the algorithm even with a few particles.[10]As explained in Lindsten, Jordan, Schon (2014), ancestor sampling breaks the reference path into pieces and this causes the particle system to collapse towards something different than the reference path. In the absence of this step, the particle system tends to collapse to the conditioning path. We employ particle Gibbs with ancestor sampling in this step to draw $X_t$.

Let $X_t^{(d-1)}$ denote the fixed the fixed trajectory, for $t = 1, 2, ..T$ obtained in the previous draw of the Gibbs algorithm. We denote the parameters of the model by $\Psi$,

[10]See Nonejad (2015) for a recent application of this algorithm.

and $i = 1, 2, ..S$ represents the particles. The conditional particle filter with ancestor sampling proceeds in the steps described below.

1. For $t = 1$
   (a) Draw $X_1^{(i)} \backslash X_0^{(i)}, \Psi$ for $i = 1, 2, ..S - 1$. Fix $X_1^{(S)} = X_1^{(d-1)}$
   (b) Compute the normalised weights $p_1^{(j)} = \frac{w_1^{(j)}}{\sum_{j=1}^{M} w_1^{(j)}}$ where $w_1^{(j)}$ denotes the conditional likelihood: $\left|\tilde{\varpi}^{-1}\right|^{-0.5} - 0.5 \exp\left(E_1' \tilde{\varpi}^{-1} E_1\right)$
2. For $t = 2$ to $T$
   (a) Resample $X_{t-1}^{(i)}$ for $i = 1, 2, ..S - 1$ using indices $a_t^{(i)}$ with $\Pr\left(a_t^{(i)} = i\right) \propto p_{t-1}^{(i)}$
   (b) Draw $X_t^{(j)} \backslash X_{t-1}^{(a_t^{(j)})}, \Psi$ for $i = 1, 2, ..S - 1$ using the transition equation of the model (equation **??**). Note that $X_{t-1}^{(a_t^{(j)})}$ denotes the resampled particles in step (a) above.
   (c) Fix $X_t^{(S)} = X_t^{(d-1)}$
   (d) Sample $a_t^{(M)}$ with $\Pr\left(a_t^{(M)} = i\right) \propto p_{t-1}^{(j)} \Pr\left(X_t^{(d-1)} \backslash X_{t-1}^{(i)}, \mu^P, \phi^P, \Sigma\right)$ where the density $\Pr\left(X_t^{(d-1)} \backslash X_{t-1}^{(i)}, \mu^P, \phi^P, \Sigma\right)$ is computed as $|\Omega|^{-0.5} - 0.5 \exp\left(\tilde{u}_{it}^{(i)\prime} \Omega^{-1} \tilde{u}_{it}^{(i)}\right)$ where $\tilde{u}_{it} = X_t^{(d-1)} - \left(\mu^P + \phi^P X_{t-1}^{(i)}\right)$. This constitutes the ancestor sampling step. If $a_t^{(M)} = M$ then the algorithm collapses to the simple particle Gibbs.
   (e) Update the weights $p_t^{(i)} = \frac{w_t^{(i)}}{\sum_{j=1}^{M} w_t^{(i)}}$ where $w_t^{(i)}$ denotes the conditional likelihood: $\left|\tilde{\varpi}^{-1}\right|^{-0.5} - 0.5 \exp\left(E_t' \tilde{\varpi}^{-1} E_t\right)$.
3. End
4. Sample $X_t^{(i)}$ with $\Pr\left(X_t^{(i)} = X_t^{(j)}\right) \propto p_T^{(j)}$ to obtain a draw from the conditional posterior distribution

We use $M = 10$ particles in our application.