Further Investigations into the Term Structure of Interest Rates

Michael J. Howell

CrossBorder Capital Ltd. and Birkbeck College, University of London

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Preface

I hereby declare that this thesis is my own work and includes nothing which is derived from collaboration; is not substantially the same as any other work I have submitted or will be submitting for a degree, diploma or other qualification, at this or any other university, and does not exceed the prescribed limit of 100,000 words.

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Michael J. Howell

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Abstract

Recent empirical term structure literature questions the usefulness of the standard three-parameter yield curve model in the wake of the Global Financial Crisis and the widespread adoption of unconventional monetary policies, such as Large-scale Asset Purchases (LSAP). This thesis builds on these concerns by extracting a new parameter from the term structure that measures the position of the traditional hump in the yield curve along the maturity axis. My alternative decomposition of the term structure makes it easier to track-down the influence of quantities on interest rates. Given that Treasuries are held as safe assets by many investor types, I interpret the new parameter as a gauge of investors' risk appetite. It is time-varying and pro-cyclical, leading the business cycle and indexes of financial stress by several months and forming part of the risk-taking policy transmission channel. My results contradict the widely-held view from event studies that LSAP reduce long-term Treasury yields. They can also explain the often divergent relative movements between Treasury term premia and the premia on risky assets, such as corporate credits.

(175 words)

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Summary

Further Investigations into the Term Structure of Interest Rates

Michael J. Howell

The interest rate term structure plays a critical role in the Neo-classical economic framework by linking together the present and the future. Applying latest mathematical and statistical techniques, the empirical literature increasingly acknowledges that it is no longer sufficient to characterise the term structure using just the standard three yield curve parameters of level, curvature and slope. In this PhD thesis, I seek to extract further information and add to existing knowledge by identifying and interpreting, to ensure is does not appear *ad hoc*, a fourth yield curve parameter, which ultimately may help to better understand the risk-taking policy transmission channel. This new parameter describes the position of the traditional hump in the yield curve along the maturity axis. Its existence has been previously recognised, but it is typically either discarded as having no economic meaning or else treated as a constant to simplify yield curve estimation. I argue here that the position of the hump contains valuable information about the risk appetite of economic agents, such as investors and credit-providers, largely because Treasury bonds represent canonical safe assets. The greater demand for safety at longer investment horizons will reduce term premia at those tenors, causing the yield curve to flatten and the position of the hump to move inwards. The position of the hump could be measured from the degree of asymmetry implicit in the pattern of term premia across the Treasury term structure. But in practice, given the absence of reliable term premia estimates, I measure the position of the hump from spot yields using a statistic I create and name D-star (for ‘distance’). A higher (lower) D-star should capture the existence of negative (positive) skew in the pattern of term premia across the yield curve; so reflect excess supply (demand) for safe assets at longer tenors and, thus, signal risk-seeking (risk-avoiding) behaviour.

By including D-star, this new yield curve decomposition makes it easier to track down the influence of quantities on the shape of the term structure. I test whether empirical estimates of D-star derived from the US Treasury market can predict future outcomes of a number of key macro-finance variables, notably the national financial stress indexes (FSIs), devised by various US Federal Reserve districts. It appears from my results that D-star consistently adds value around a year ahead. This suggests that D-star could be included among the array of variables regularly monitored for financial stability purposes. I subsequently proceed, in the final section of this thesis, to use these D-star estimates empirically to better understand policy transmission in the wake of the 2007/08 Global Financial Crisis and Great Recession (GFC) and the subsequent Large-scale Asset Purchases (LSAP) policy response. LSAP should cause D-star to fall-back alongside declining term premia, as is apparently shown by a large number of recent event studies. Paradoxically, I demonstrate the opposite result: LSAP policies ultimately have a positive effect on risk appetite and lengthen D-star. This, I argue, is because LSAP are multi-faceted: the signalling and liquidity impacts of LSAP on the demand for government bonds outweigh any scarcity and duration effects. Tracing thought the transmission channels using a Bayesian vector auto-regression (BVAR) model, these positive effects appear to be encouraged by second-round influences based on lower perceived systemic risks, explained by Treasuries being held as safe assets by many investors. In other words, the cash injections that are associated with a decrease in the effective supply curve for maturity subsequently induce an offsetting fall in the demand curve. Using this risk-taking transmission channel, I argue that LSAP ultimately result in higher (not lower) Treasury term premia, steeper (not flatter) yield curves and higher (not lower) long-term yields. My framework also helps to understand the apparent negative correlation between corporate debt spreads and Treasury term premia, because risk-seeking investors switch from safe to more risky assets. This outturn is time consistent with policy-makers' original intentions to encourage greater risk-taking following the GFC. My empirical results suggest that changing risk appetite has the greater impact on corporate credit spreads, whereas the liquidity effect from LSAP is a more important determinant of Treasury term premia. The existence and measurement of D-star facilitate this re-interpretation.

Supervisors: Dr. David Schroeder/ Dr. Roald Versteeg

Titles: Lecturers in Finances, Birkbeck College, University of London

Contents

Preface ... i
Abstract ... ii
Acknowledgements ... iii
Summary: Further Investigations into the Term Structure of Interest Rates. ... iv
List of Tables ... viii
List of Figures. ... ix
1 Introduction: The Interest Rate Term Structure ... 1
2 Background: The Expectations Hypothesis, Duration, Immunization, Safe Assets and the Empirical Term Structure Literature ... 6
2.1 The Expectations Hypothesis ... 6
2.2 Review of the Empirical Term Structure Literature ... 7
2.3 Duration ... 9
2.4 Immunization and the Demand for Safe Assets ... 12
Appendix
Decomposing the Yield Curve ... 15
3 A New *Preferred Habitat* Yield Curve Parameter ... 19
3.1 Introduction ... 19
3.2 Review of the Preferred Habitat and Institutional Finance Literature ... 25
3.3 Duration Management and the Demand and Supply for Maturity ... 28
3.4 An Intuitive Explanation of D-star Using the Quadratic Yield Curve ... 33
3.5 D-star: Measuring the Position of the Yield Curve Hump ... 35
3.6 Data Description ... 38
3.7 Estimation of D-star. ... 40
3.8 A Comparison with Principal Components and Kalman Factors ... 46
3.9 Conclusion ... 49
Appendices
3A: An Interpretation of the Position of the Yield Curve Hump ... 52
3B: US Treasury Term Structure 30th December 2012 ... 54
3C: The Affine Term Structure Model ... 62
3D: US Treasury Yield Curve Methodology ... 66

4 Using the Interest Rate Term Structure to Model Risk-Seeking Behaviour and Predict Future Financial Stress 67

4.1 Introduction 67

4.2 Financial Stress Indexes and Risk Appetite Data 69

4.3 Granger Causality Tests 71

4.4 Testing Prediction using Bayesian Information Criteria.......................74

4.5 Out of Sample Tests 83

4.6 Event Studies – The Y2K Bubble and The Global Financial Crisis 85

4.7 Conclusion 88

Appendix

Granger Causality Test Results 90

5 Do Central Bank Asset Purchases Drive Treasury Yields Higher or Lower? – An Investigation of the Risk-Taking Policy Transmission Channel 96

5.1 Large-Scale Asset Purchases and Risk Premia 96

5.2 Event Studies...100

5.3 Review of Transmission Channel Literature.......................................105

5.4 Quantifying the Effects of Liquidity and Risk Appetite 110

5.5 Data Description..113

5.6 Estimation Results...115

5.7 Conclusion 124

Appendices

5A: Table 1, Major Actions and Statements Concerning Federal Reserve Large Scale Asset Purchases (LSAP)...127

5A: Table 2, 'Forward Guidance' in FOMC Statements Issued From Late-2008 to 2013..128

5B: Impulse Response Functions 129

6 Concluding Remarks 133

References 133

List of Tables

3.1 Cross-Correlation Coefficients between Yield Curve Factors, 1987-2016 20

3.2 Cross-correlations (15 months ahead) and Granger Causality Tests (12 months) between US Financial Stress Index and High Yield Spread with various Yield Curve Factors, 1987-2016..21

3.3 Summary Statistics – Various Estimates D-Star, 1946-2016 40

3.4 Correlation Coefficients –Estimates D-Star and D-Peak, 1989-2016...............................42

3.5 US Treasury Yield Curve Classified by Slope, Curvature and D-star, 1946-2017...........43

3.6 Regression of Selected US Treasury Yields on Various Yield Curve Factors, 1954-2016..47

4.7 Granger Causality Tests – Summary Results...73

4.8 Regression of First Principal Component of Major US National Financial Stress Indexes on Principal Components of the US Treasury Yield Curve, with and without D-star, for various lead-times (3, 6, 9, 12, 15 and 18 months), 1994-2016 75

5.9 Estimated Effects of Quantitative Easing (LSAP) on 10-year Bond Yields...................102

List of Figures

2.1 Present Value Cash Flow Profiles of Three Assets and Their Duration 13

3.2 D-Star (Position of Curvature Peak in Years, 6-month CMA, Advanced 15 months and Inverted) and B-BBB Corporate Credit Spread, 1987-2016 23

3.3 Liability Duration and Fixed Income Portfolio Duration – Sample of Major US Pension Funds, 2011-16 30

3.4 The Average Maturity of US Treasury Securities Outstanding, 1946-2016; the Average Maturity of Federal Reserve Holdings, 2003-16 and Duration of Aggregate US Treasury Bond Index, 1980-16 32

3.5 Yield Curve – Level, Slope, Curvature and Position 34

3.6 Maturity of Average Curvature (D-star) – Security-level and Generic US Treasury Yields, 1989-2016 41

3.7 D-star (6-month CMA) and Yield Curve Slope (10-1 year), 1946-2016...........................44

3.8 D-star (6-month CMA) and Curvature (10-5-1 year), 1946-2016 45

3.9 D-star (6-month CMA) and a Fourth Kalman Factor Filtered from Affine Yield Curve, 1982-2016..49

4.10 First Principal Component of Major Financial Stress Indexes (FSIs), 1994-2016..........76

4.11 US Corporate Spreads, 1987-2016..77

4.12 Financial Stress Indexes (FSIs) and Bond Risks, 1994-2016 78

4.13 University of Michigan US Consumer Sentiment Survey, 1985-2016............................78

4.14 US Business Activity, 1954-2016 80

4.15 USM Index 1954-2016 and 2000-2016 80

4.16 BIC Tests on Risk Appetite Using Three Benchmarks, various time periods 81

4.17 US High Yield Spread (B-Baa) – Actual and Out-of-Sample Forecasts, 2004-16...................84

4.18 US Consumer Sentiment (University of Michigan) – Actual 12 month change and Out-of-Sample Forecasts, 2004-16 84

4.19 Global Risk Appetite (ECB Measure) and D-star (inverted, advanced 12 months), 2006-2010 85

4.20 Y2K Bubble Finance Crisis – D-star (Advanced) and Selected Macro-Finance Variables, 1999-2003 86

4.21 Global Finance Crisis – D-star (Advanced) and Selected Macro-Finance Variables, 2006-10 87

5.22 US QE Periods, Nominal Term Premia and 10-Year Treasury Yield, 2007-15 98

5.23 US Treasury Nominal Term Premia and LSAP Announcement Effects, 2008-2012....101

5.24 US Corporate Credit Risk Premia (Junk CCC less High Yield Single B and High Yield (B) less Investment Grade (BBB)) and LSAP Announcement Effects, 2008-2012 101

5.25 D-star (Implied Risk Appetite) and LSAP, 2007-16..114

5.26 Selected Impulse Response Functions 117

5.27 The Risk-Seeking Channel (Schematic) 119

5.28 Comparative Impulse Responses to D-star and Liquidity Shocks – 10-year Treasury Term Premia and B-BBB Credit Spreads 121

5.29 Robustness Tests – Effects on IRFs of Dropping Lags and Restricting Sample Size 123

Chapter 1

Introduction: The Interest Rate Term Structure

"...yield quotations must appear as a bewildering welter of unrelated interest rates. Yet this seeming jumble of rates is not without order." Jacob B. Michaelsen, The Term Structure of Interest Rates (1973)

The recent Global Financial Crisis and Great Recession (GFC) have focussed attention on the stability of the balance sheet structures of investors; the efficacy of subsequent zero-interest rate policy response (ZIPR) and the implementation and transmission of Large-scale Asset Purchases (LSAP). This thesis analyses the US Treasury interest rate term structure in this light. The term structure is central to the Neo-classical economic framework by linking the present with the future. It is traditionally characterised just by its level, slope and curvature. However, I identify a fourth parameter, based on the position of the hump in the yield curve along the maturity dimension, which adds new information and makes it easier to track down the influence of quantities on the shape of the term structure.

My starting point is an attempt to devise a practical measure of the implicit distribution of term premia across the Treasury term structure based on its degree of asymmetry. The position of the traditional hump in the yield curve along the maturity axis (i.e. the additional parameter) should characterise the distribution of term premia across tenors. I term this new parameter, D-star, and show that it can be easily calculated for all yield curve types using a simple distance measure. D-star estimates for the US are later cross-checked with a Kalman filtered factor. Although it is statistically significant, D-star does not add much in economic terms to the explanation of the current yield curve beyond that already known from the three traditional yield curve factors. However, it contains other information about the risk appetite of investors, which is relevant for the predictability of future yields. In fact, the general existence of unspanned macro-factors that improve prediction has been studied by Coroneo et al. (2016). My approach differs because I argue that D-star also helps to forecast broader macro-finance variables, such as a composite US financial stress index (FSI) and the high yield credit spread (B less BBB-rated corporate bonds), approximately one year ahead. My results demonstrate significant one-way Granger causality for this new parameter, compared to the other yield curve factors. I go on to show that D-star allows a better understanding of the policy transmission mechanism, given the low importance assigned by Bernanke and Blinder (1992) to interest rates, and its existence enables us to more clearly delineate the *risk-taking channel* from the *credit channel*.

It seems plausible that more distant (nearer) yield peaks in the term structure reflect relatively larger term premia at longer (shorter) time horizons. Intuitively, these should identify risk-seeking behaviour, because the demand for Treasury securities is a derived-demand for safe assets by many investor types. Safety is here defined in terms of a preferred habitat, based either on regulation needs or on duration and minimum liquidity requirements. Excess safe asset supply (demand) at any maturity will raise (lower) local term premia, resulting in *limits to arbitrage*. Hence, risk-seeking (avoiding) behaviour should lead to an excess supply of (demand for) Treasuries at longer horizons and so raise (depress) more distant term premia, causing a steeper (flatter) yield curve; a negatively (positively) skewed distribution of term premia and a yield curve hump positioned at a longer (shorter) tenor.

Recent large-scale asset purchases (LSAP) by Central Banks, in the wake of the 2007/08 Global Financial Crisis and Great Recession (GFC), and the growing safe asset demands from foreigners and domestic financial institutions, following new regulations, have disrupted the normal balance between supply and demand in the US Treasury markets. The effects of these quantitative imbalances, which are absent from the standard finance models, are likely to be felt across the interest rate term structure. When changes to the effective supply of government securities (including LSAP) distort local term premia, these scarcity effects may simply inconvenience certain investors and have a limited macro-economic impact beyond lowering average term premia and, hence, average Treasury yields. However, when these imbalances are driven by demand factors, they may tell us something about investors' risk appetites. I treat this as an empirical question, albeit one also faced when interpreting the standard yield curve factors. One complication is that changes in the authorities' net supply function may themselves induce fluctuations in the demand functions of investors because they potentially signal future policy intentions ('Forward Guidance') as well as providing extra liquidity ('Quantitative Easing'). Taken together these responses may reduce perceived systemic risks[1].

A proper evaluation of these effects is made difficult because of a lack of data on the supply of bonds and investor demands across the various maturities and the widespread scarcity of reliable term premia data. These observations motivate the three core chapters of this thesis. These try to extract further quantitative information from the term structure, with a focus on implementing a practical estimation method for D-star, and then applying it to predict future financial stress and better understand the transmission of monetary policy. My key contributions in this thesis are:

- Measurement: The third chapter *A New 'Preferred Habitat' Yield Curve Parameter* introduces a measure of the position of the traditional hump along the maturity axis, termed D-star, that implicitly describes the cross-sectional pattern of term premia across tenors. This may also be the point where the curvature of the term structure peaks. Term premia are by implication relatively smaller at subsequent maturities. I use the *preferred habitat* framework of Vayanos and Vila (2009) and adapt the 'gap filling' model of Greenwood, Hanson and Stein (2010) to explain D-star. Low Treasury term premia at longer maturities suggest a smaller D-star value. This could reflect an excess demand for safety at those tenors, implying a reduced risk appetite among investors. Investors' risk appetite is here defined in terms of deviations away from a risk-neutral duration point and calculated from the inflection point on the yield curve using a standard average distance measure. It might be described by market participants as the

[1] It could be argued from a supply perspective that any lengthening in the average maturity of government debt, by postponing the need for subsequent re-financing, also reduces systemic risks.

‘duration-weighted average butterfly spread across tenors’. I explicitly do not use term premia estimates for this calculation. The derived factor represents a fourth yield curve parameter and is a convenient measure of the investment time horizon. The values of D-star are cross-checked with alternative Kalman filter estimates. The resulting data are time-varying, with a mean of 6.3 years (1946-2016) and a standard deviation of 10-months.

- Evaluation: Chapter 4 *Using the Interest Rate Term Structure to Model Risk Seeking Behaviour and Predict Future Financial Stress* tests the efficacy of D-star as a warning sign of future financial stress, using officially published financial stress indexes (FSIs) and their key constituents (Hakkio and Keeton, 2009). D-star tends to rise ahead of financial booms and to fall ahead of financial crises and economic recessions. D-star appears to Granger cause standard measures of US economic activity and risk premia, and it adds information 12-15 months ahead over conventional benchmarks, according to Bayesian Information Criteria (BIC), out-of-sample predictions and event studies.

- Transmission: The fifth chapter *Do Central Bank Asset Purchases Drive Treasury Yields Higher or Lower?* explores the economic and financial transmission of these *risk appetite* effects in more detail, using a Bayesian VAR framework similar to Rey (2016). This sees LSAP as one part of the *risk-taking channel* of monetary policy (Borio and Zhu, 2012) and explicitly tries to model the relative movements between Treasury term premia and other risk premia, such as corporate credit spreads. Variance decomposition suggests that risk appetite has the greater impact on credit spreads, whereas LSAP is a more important determinant of term premia. Here, I reach opposite conclusions from many recent event studies (Gagnon, 2016), insofar that LSAP ultimately result in larger not smaller Treasury term premia. This I explain from the second-round effect that the extra liquidity injections associated with LSAP have in eliminating systemic risks and so reducing investors’ demands for safety.

The existence of D-star motivates a new term structure decomposition that makes it easier to track-down the influence of quantities on current and future interest rates. I conclude that the possible scarcity and duration effects from LSAP in reducing the effective supply of safe assets are overwhelmed by stronger confidence effects, signalled by ‘forward guidance’ and extra liquidity. These second-round influences are based on lower perceived systemic risks, given that Treasuries are held as safe assets by many investors. Thus, I use this risk-taking transmission channel to argue, contrary to most recent event studies, that LSAP ultimately result in higher (not lower) Treasury term premia, steeper (not flatter) yield curves and higher (not lower) long-term yields. Hanson, Lucca and Wright (2017) explain this same phenomenon using a slow-moving arbitrage capital model which allows the demand curve for maturity to become more elastic over-time. My different explanation is that the cash injections associated with the LSAP cause the demand curve for maturity (with respect to yields) to shift backwards. Moreover, my model is also able to rationalise the apparent negative correlation between corporate debt spreads (risk assets) and Treasury (safe assets) term premia. This result is likely time consistent with policy-makers original intentions to encourage greater risk-taking, following the 2007/08 Global Financial Crisis (GFC). The existence and measurement of D-star facilitate this re-interpretation.

Chapter 2

Background: The Expectations Hypothesis, Duration, Immunization, Safe Assets and the Empirical Term Structure Literature

2.1 The Expectations Hypothesis

This chapter provides background information on the standard expectations hypothesis model of the term structure and reviews the recent empirical term structure literature. It also defines duration and immunization and what constitute safe assets, concepts that later feature as factors that influence investors' demand for bond maturity.

The term structure of interest rates, or yield curve, traditionally expresses the spot yield on a default-free government bond across a cross-section of horizons that describe the notional maturity date of each bond[2]. The spot yield is the redemption yield[3] of a zero-coupon bond. It comprises the product of one-period forward rates, i.e. the discount rate of a single cash flow from a zero-coupon bond equivalent, over a fixed holding period. Each spot yield (y_t^m) comprises an expected real interest rate (R_t) plus an expected inflation rate (π_t) over a holding period (m) plus a nominal term (or bond maturity risk[4]) premium (tp_t^m). Under the *expectations hypothesis* (EH), the nominal term premia are constant for all horizons (m). In the case of the pure expectations hypothesis (PEH), they are zero across all horizons (m). According to efficient markets theory, these risk premia should be negligible. The expectations theory of interest rates can be described from the following equation, after making the appropriate term premia assumptions:

[2] US Treasury notes are issues with maturities of two, three, five, seven, and 10 years, while Treasury bonds have maturities of 20 and 30 years: the only difference between notes and bonds is the length until maturity. Treasury bills are short-term bonds that mature within one year or less from their time of issuance.

[3] Or yield-to-maturity

[4] Bond analysis involves several risk dimensions including illiquidity, default and duration. Traditionally, default-free, liquid government bonds have a single risk or term premia, based on their period to redemption.

$$y_t^m = \frac{1}{m}\sum_{i=0}^{m-1} E_t R_{t+i} + \frac{1}{m}\sum_{i=1}^{m} E_t \pi_{t+i} + tp_t^m \quad (1)$$

where y_t^m is the spot yield of a bond of maturity m at time t; E_t denotes the expectations operator; R_t is the real interest rate; π_t is the inflation rate; tp_t^m represents the nominal bond term premium over a holding period m

Although government bonds are typically assumed to be default-free, private sector bonds have associated default risks. The quality of these credits is evaluated by independent agencies, such as Moody's and Standard & Poors, who assign ratings to each bond (e.g. AAA, B, etc). Junk bonds are considered to have a CCC-rating or above, and investment grade bonds a BBB-rating or better[5]. So-called *high yield bonds* have a B-rating. The yield spreads between these different bonds measure their risk premia. These can set either against default-free government bonds or higher quality equivalent private bonds, e.g. BBB less B.

2.2 Review of the Empirical Term Structure Literature

The recent empirical term structure literature broadly divides into two branches and from there splits into a number of sub-branches. The first branch describes attempts to reduce the dimensionality of the term structure data, while the second investigates the two-way relationship between bond yields and macro-economic variables. The former, in turn, can be divided into three: (a) factor models, such as Litterman and Scheinkman (1991) and Ilmanen (1995); (b) parametric models, such as Nelson and Siegel (1987); Diebold and Li (2006), and BIS (2005), and (c) affine-type models (a constant plus linear function of latent factors), which impose no-arbitrage conditions, and their antecedents, such as the Vasicek (1977) single-factor model and the multi-factor approaches of Cox, Ingersoll, and Ross (1985), Dai and Singleton (2000), where tractability arguably comes at the cost of poor empirical prediction (Duffee, 2002). However, the affine approach of Kim and Wright (2005) is favoured by Swanson, Rudebusch and Sack (2007) as a way of extracting historic term premia. The second

[5] The Moody's 'Baa' investment grade is equivalent to S&P's 'BBB' rating.

branch can, in turn, be sub-dived into analyses of the effect of: (a) yield curve factors on macro-economic variables, such as Estrella and Hardouvelis (1991), Moench (2012) and Tobin (1958, 1969) and (b) macro-economic factors on the yield curve, such as Modigliani and Sutch (1966), Vayanos and Vila (2009), Greenwood and Vayanos (2009), Krishnamurthy and Vissing-Jorgensen (2011), Ang and Piazzesi (2001), Diedold, Rudebusch and Aruoba (2006), Ludvigson and Ng (2009) and Fontaine and Garcia (2011). Although my research has affinities with this second branch, by attempting to extract a fourth yield curve parameter from the term structure data and improve factor modelling, it properly belongs to the first sub-group of the first branch.

The traditional level, slope and curvature decomposition of the yield curve is often derived from principal components and forms part of the *arbitrage pricing theory* (APT) literature (see Ross, 1976). Principal components are eigenvectors that seek to establish independent clusters of common variation. According to Cochrane and Piazzesi (2005), the first three principal components explain over 99% of the variation across the term structure. Following Litterman and Scheinkman (1991), these components are intuitively interpreted as *level, slope* and *curvature* because of the pattern of their loadings. However, Lord and Pelsser (2007) argue that in circumstances common to bond markets, this interpretation is an artefact of the data and not necessarily robust. It is far from certain that the three components correspond to their eponymous labels, since, for example the first principal component will include effects from the joint correlations between slope and level and between curvature and level. Disaggregating the data sample by decade, shows that although the absolute size of the three principal component loadings are remarkably constant, the slope loadings alter their signs, perhaps signalling changes in the slope of the yield curve, while the peak curvature loading switches between maturities. Through the 1946-49 immediate post-war years, the one-year bond enjoyed the largest loading; during the 1950s and 1960s as economies strengthened, the third principal component was most heavily loaded on to the five-year maturity; in the 1970s credit boom this had moved out to the seven-year maturity, but through the 1980s, the loading on the three-year bond was heaviest; the 1990s saw a return to the five-year maturity; it rose to seven years in the 2000s, but then dropped back to the three-year maturity after 2010, in the wake of the Great Recession.

Hanson, Lucca and Wright (2017) similarly conclude that these principal components are unstable over time.

According to the literature, the yield curve is typically upward-sloping and, contrary to the expectations hypothesis (Lutz, 1940), has a time-varying *ex post* term premia on longer-dated bonds (Fama and Bliss, 1987; Campbell and Shiller, 1991; Cochrane and Piazzesi, 2005). It finds this difficult to justify economically (Campbell, Lo and MacKinlay, 1997), because the standard yield curve is ideally constructed under assumptions of supply and demand elasticity; market clearing; perfect substitutability between bonds of different maturities; full arbitrage and with homogeneous investors (see Cox, Ingersoll and Ross, 1985, among others). In addition, the method of Treasury financing is assumed to have no impact on consumption for Ricardian reasons; hence it cannot affect the future interest rate path. The term structure is then entirely determined by the current level and expected path of the policy rate, with quantities and the maturity composition of Treasury supply having no significant effect on yields. Non-price factors, namely maturity, duration and quantity effects, comprise part of the growing literature on financial frictions that originated with liquidity preference (Hicks, 1946) and market segmentation (Culbertson, 1957), but they do not feature in standard yield curve models.

2.3 Duration

Duration is a concept taken from finance. It measures the effective life-span of a capital project from its expected pay-off structure, usually expressed in years. In contrast to maturity, which only considers the final payment from an investment, duration gives weight to all cash flows received (paid-out), e.g. coupons, over the entire life of the asset (liability), taking into account both size and frequency of payment. These cash flows need to be evaluated in similar terms and so it seems correct to use present value calculations and to focus on actual or expected cash payments in a common currency. When calculating this investment time horizon, it makes economic sense to include all future cash payments over the life of each project and not just the final payment, as with maturity data. The resulting payment patterns need not be smooth, but they should have a finite or limiting sum and possess an expected value. When the present values of these cash payments are used to weight time periods one gets *Macaulay duration*, a concept related to *semi-elasticity* in economics (Macaulay, 1938) and to *modified duration* (see Appendix A). It can be formally defined:

> <u>Definition</u> *Macaulay duration:* the cash flow-weighted average time period (usually measured in years) to receive (or pay-out) all future cash flows, including dividends, coupons and capital repayments.

For any asset this is:

$$MD_t = \frac{\sum_{\tau=1}^{\tau=M} E_t \left[\frac{\tau \cdot C_{t+\tau}}{(1+k_{t+\tau})^{t+\tau}} \right]}{\sum_{\tau=1}^{\tau=M} E_t \left[\frac{C_{t+\tau}}{(1+k_{t+\tau})^{t+\tau}} \right]} \qquad (2)$$

where $E_t(.)$ is the expectations operator; MD_t is Macaulay duration in period t; M is maturity and for many assets this is unbounded, so $M=\infty$; $C_{t+\tau}$ the net cash receipt in period $t+\tau$ and k_t the discount rate, and $k_t=r_t+h_t$, where r_t denotes the risk-free rate at period t and h_t is the term premium[6].

The expression can be re-written as a weighted average of future time periods extending over a horizon M, where the weights are the proportions of total present value that occur in each period.

Thus:

$$MD_t = \sum_{\tau=1}^{\tau=M} w_{t+\tau} \cdot \tau$$

where

$$w_{t+\tau} = E_t \left[\frac{\frac{C_{t+\tau}}{(1+k_{t+\tau})^{t+\tau}}}{\sum_{\tau=1}^{\tau=M} \frac{C_{t+\tau}}{(1+k_{t+\tau})^{t+\tau}}} \right]$$

[6] In practice, changes in k only have a small effect on the value of bond duration (MD), so that it is typically taken as a constant.

And the weights sum to one:

$$\sum_{\tau=1}^{\tau=M} w_{t+\tau} = 1$$

In the case of a very long-term bond, the importance of the distant maturity date on the duration value may be small or even negligible. For example, a 3.5% coupon bond, yielding 6% to maturity and with as long as 100 years until its redemption date has duration of only 16.8 years[7]. It can be shown that a perpetual bond has duration equal to $(1+k_t)/\ k_t$. Duration is a particularly useful life-span measure for securities other than bonds that have no fixed, no finite and no certain repayment schedule and typically may also have no legal obligation to return the principal. Duration is always bounded from above by maturity and it is similar to the concept of 'useful life' implemented by tax authorities to measure economic depreciation schedules for productive assets, where economic life is linked to the likely period of greatest revenue generation. The US IRS, for example, deems airplanes and computers to have six year working lives for tax purposes, whereas water utilities can be written-off over 50 years.

Although Macaulay (1938) originally devised his duration measure to calibrate and compare US railroad bonds of different credit qualities, duration is most often calculated for individual bonds where the cash flows (C_t) and the discount factors (k_t) are known over time. Consequently, duration (D_t) for these individual securities is typically thought of as a fixed number. However, for portfolios and for the entire economy, not only will cash flows and discount factors vary over time, but so will the mix of instruments. This makes aggregate asset duration for both portfolios of securities and for the entire economy potentially variable from differences in: (1) cash flow timing; (2) cash flow uncertainty (i.e. discount factor) and (3) the mix of assets in the portfolio. These duration differences can be seen from Figure 1, which depicts the present value cash flow patterns of three assets A, B and C. The sum of the respective present values defines each asset value (denoted in Figure 1 by $\sum PV_{A,t} = A$, etc). Each

[7] Macaulay duration: take the example of a par bond yielding an annual $10 coupon. Assume it is redeemed in three years and the annual discount rate is 8%. The present value (PV) of cash receipts is $10+10/(1.08)+110/(1.08)^2$ and the time-weighted present value (TPV) is $1\cdot10+2\cdot10/(1.08)+3\cdot110/(1.08)^2$. The ratio of these sums (TPV/PV) gives Macaulay duration of 2.74 years (=311.44/113.57).

of the assets have different durations D_A, D_B and D_C, but assets A and B share the same time to maturity, M. By measuring the average timing of cash payments and cash receipts, duration is closely related to liquidity, which I here define as the ability to meet all contractual obligations as they fall due. Illiquidity, therefore, implies a duration mis-match between assets and liabilities. Liquidity is a more exacting condition than solvency since some agents can be solvent overall, but still illiquid in specific periods. Unanticipated cash payouts can often pose a threat and an appropriate cushion of liquid/ zero duration assets, such as US Treasuries, may need to be held to mitigate this risk.

2.4 Immunization and the Demand for Safe Assets

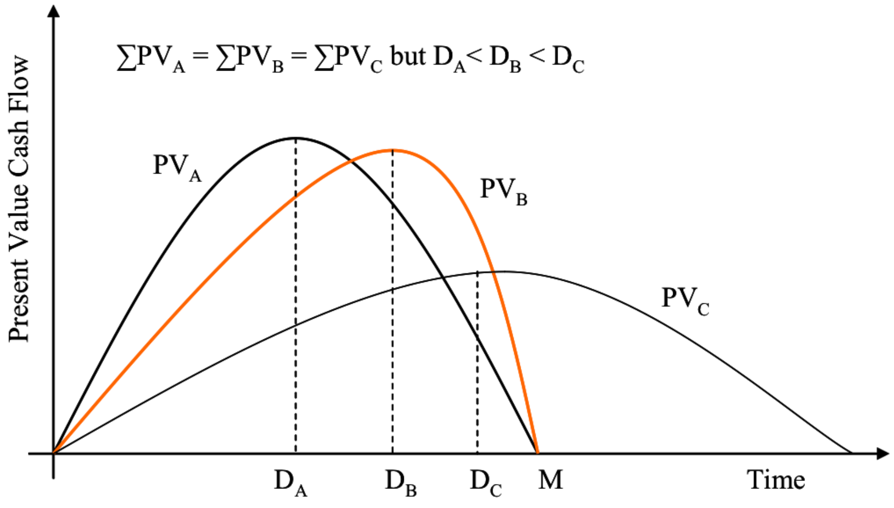
Duration can be aggregated in a straightforward way across assets to give portfolio duration and, under certain assumptions about investors' preferences, across their liabilities to give a duration target for a group (Chiappori and Ekeland, 2011). Investors may not view displacements away from this duration target equally. At different times, deviations below the duration target may be viewed more favourably than deviations above it. For example, it is known from the literature (Cochrane and Piazzesi, 2005) that low duration investments, such as cash, may be more valued when the marginal utility of money is high, such as in a recession. Assets are held to meet future liabilities. When asset ($D_{A,t}$) and prospective liability duration ($D_{L,t}$) are matched at this preferred habitat point, liabilities are said to be *immunized*[8]. I assume that this point represents an equilibrium, where the investor faces no duration risk, no illiquidity risk and no re-investment risk[9]. Wachter (2003) confirms that ten-year bonds are safer than one-year bonds for risk-averse investors with ten-year investment horizons. Equilibrium is restored following shocks by an incentive not to incur the costs of any duration mismatch, such as a short-fall of asset values following a change in discount rates. Immunization is akin to avoiding a maturity mis-match between assets and liabilities,

[8] The literature contains two definitions of *immunization*: (1) *partial*, where the interest rate sensitivities of assets and liabilities are matched, and (2) *complete*, where the cash flow needs of liabilities are matched by the investments. *Modified duration* (D_t) is traditionally used to *partially immunize* portfolios. $D_t\ (1+k_t)=MD_t$ See Appendix A.
[9] *Re-financing risk*, which measures the ability to roll-over positions, is also termed *liquidity risk* in the literature and can describe a safety channel of monetary transmission. CFOs responding to the Graham and Harvey survey cited 'refinancing in bad times' a major reason for extending debt maturity. *Duration risk* measures the aggregate sensitivity of bond values to interest rate shocks and it rises in proportion to duration.

such as that frequently faced by banks, but recast more generally for all investors and for all assets, not just zero-coupon bonds, in terms of duration.

In a World of complete markets and perfect foresight, duration risk should not matter because agents facing future known liabilities are able to purchase notional zero coupon assets that mature with certain payment on the specified dates. In other words, these agents are always perfectly *immunized*, indifferent to volatility and unaffected by discount rate shocks. However, where there are incomplete markets, including a lack of securities with the appropriate durations, or frictions, such as transactions costs, and when liability duration is either uncertain or itself likely to change, then discount rate shocks matter and duration management becomes important. This explains the commercial existence of a large and active duration management industry. Impetus to immunize assets also comes from the US Pension Protection Act of 2006, which requires more frequent assessments of funding shortfalls, and the Financial Accounting Standards Board (FASB) ruling that any funding shortfall in US corporate pension plans must be reflected in a lower reported balance sheet net worth.

Figure 1: Present Value Cash Flow Profiles of Three Assets and Their Durations



The diagram shows the theoretical present values of cash inflows for three assets: A, B and C. The sums of present values are equal for each asset. The maturity of assets A and B are also the same, but asset C has a longer maturity. The durations reflect the ‘centre of gravity’ of each present value distribution. These differ for each asset as shown.

Safe assets can be defined as assets that fulfil these immunization needs, while simultaneously meeting minimum liquidity requirements. According to the IMF (2012), a *safe asset* is a financial instrument that provides: (1) low market and credit risks; (2) high market liquidity; (3) limited inflation risks; (4) low exchange rate risks and (5) limited idiosyncratic risks. It will likely correlate negatively with investors' risk appetite. The canonical safe asset is the 10-year US Treasury note, but the list includes all assets that are used in an information-insensitive fashion (Gorton et al, 2012). The supply of these assets is not perfectly elastic and may have an associated cost similar to the 'Triffin Dilemma' (Portes, 2013). Supply shortages of safe assets can occur because of regulation, Central Bank LSAP, credit rating agency downgrades and falls in investors' risk appetite. It is suggested in the literature that shortages in the supply of safe assets lead to macroeconomic disequilibria and greater financial stress (Caballero, 2006). Krishnamurthy and Vissing-Jorgensen (2013) specifically claim that the increasing supplies of US Treasuries reduce the probability of financial crises.

Appendix: Decomposing the Yield Curve

I use an established method to factorise the yield curve. See, for example, Ilmanen (1995). Let y_1 denote one period spot rates; y_t is the spot rate in period t; h_n is the one period holding period return of an n-year bond; rp_n the risk premium for an n-period bond; $f_{n-1,n}$ the one period forward rate between n-1 and n; $P_{n,t}$ is the price on an n period bond; $P_{n,t+1}$ denotes the price next period; D_n represents duration for an n-period bond; Cvx_n is convexity and V denotes volatility.

One period holding period returns for an n-period zero coupon discount bond are:

$$h_n = \frac{P_{n-1,t+1} - P_{t,n}}{P_{n,t}}$$

This can be re-written:

$$h_n = \frac{(P_{n-1,t+1} - P_{n-1,t}) + (P_{n-1,t} - P_{n,t})}{P_{n,t}}$$

Dropping the time period subscripts for convenience, this becomes:

$$h_n = \left(\frac{\Delta P_{n-1}}{P_{n-1}} \cdot \frac{P_{n-1}}{P_n}\right) + \frac{(P_{n-1} - P_n)}{P_n} \qquad (A1)$$

By definition:

$$\frac{P_{n-1}}{P_n} = \frac{(1 + y_n)^n}{(1 + y_{n-1})^{n-1}} = 1 + f_{n-1,n} \qquad (A2)$$

The percentage change in the bond price can be approximated by a Taylor expansion:

$$\frac{\Delta P_n}{P_n} = -D_n \cdot (\Delta y_n) + 0.5 \cdot Cvx_n \cdot (\Delta y_n)^2 \qquad (A3)$$

Where *modified duration* (D) and convexity (Cvx) are, respectively, defined as:

$$D = \frac{dP}{dy} \cdot \frac{1}{P}$$

Note: *Modified duration* (D_n) for an n-period bond is related to *Macaulay duration* (MD_n), where ytm_n is the yield to maturity, or in this case the spot yield (y_n) by:

$$D_n = (1 + ytm_n)MD_n = (1 + y_n)MD_n$$

And:

$$Cvx = \frac{d^2P}{dy^2} \cdot \frac{1}{P}$$

Which is often written as:

$$Cvx_n = D_n^2 - \frac{dD_n}{dy_n}$$

Combining equations *A1*, *A2* and *A3* gives:

$$h_n \approx f_{n-1,n} + \left(1 + f_{n-1,n}\right) \cdot [-D_{n-1} \cdot (\Delta y_{n-1}) + 0.5 \cdot Cvx_{n-1} \cdot (\Delta y_{n-1})^2]$$

Taking expectations of both sides and noting that for volatility (V): $E(\Delta y_n)^2 \approx V(\Delta y_n)^2$:

$$E(h_n) \approx f_{n-1,n} + \left(1 + f_{n-1,n}\right) \cdot [-D_{n-1} \cdot E(\Delta y_{n-1}) + 0.5 \cdot Cvx_{n-1} \cdot (V(y_{n-1}))^2]$$

The one period forward rate equals the zero's rolling yield. In turn, this consists of the running yield plus the, so called, *roll-down return* that comes from the maturity-driven period-to-period fall in yields. Thus, the above expression shows that the one period holding period return can be broken down into: (a) the running yield; (b) the roll-down return plus the duration impact of the interest rate view, and (c) the value of convexity.

Subtracting the one period riskless rate (y_1) from both sides defines the bond risk premium:

$$E(h_n - y_1) \approx (f_{n-1,n} - y_1) + \left(1 + f_{n-1,n}\right) \cdot [-D_{n-1} \cdot E(\Delta y_{n-1}) + 0.5 Cvx_{n-1}(V(y_{n-1}))^2]$$

Rearranging this expression shows that the steepness of the one year forward curve ($Fwsp_n$) comprises (a) the bond risk premium (rp_n); (b) the duration impact of the rate view and (c) a convexity effect:

$$f_{n-1,n} - y_1 \approx E(h_n - y_1) - \left(1 + f_{n-1,n}\right) \cdot [-D_{n-1} \cdot E(\Delta y_{n-1}) + 0.5 Cvx_{n-1} \cdot (V(y_{n-1}))^2]$$

Or:

$$Fwsp_n \approx rp_n + \left(1 + f_{n-1,n}\right) \cdot [D_{n-1} \cdot E(\Delta y_{n-1}) - 0.5 \cdot Cvx_{n-1} \cdot (V(y_{n-1}))^2]$$

And where:

$$f_{n-1,n} \approx \frac{n \cdot y_n - (n-1) \cdot y_{n-1}}{n - (n-1)}$$

$$f_{n-1,n} \approx n \cdot y_n - (n-1) \cdot y_{n-1}$$

The risk premium shown above is also called the bond term premia. It can be variously defined in terms of yields, forwards or expected returns, although each is connected. It is conventional to think of the risk premium as the difference between the expected one period holding period return from an n-term investment and cash (or here a one-year spot yield, $y_{1,t}$):

$$rrp_{n,t} = E_t\left(h_{n,t+1}\right) - y_{1,t}$$

$$xr_{n,t+1} = h_{n,t+1} - y_{1,t}$$

and when expectations are realised, $E_t(h_{n,t+1}) = h_{n,t+1}$, then $xr_{n,t+1} = rrp_{n,t}$ where $rrp_{n,t}$ is the return risk premium.

The yield risk premium can be equivalently expressed as a sum of excess returns of declining term, which can be seen to be the average of expected future return risk premia per period:

$$yrp_{n,t} = y_{n,t} - \frac{1}{n} E_t\left(y_{1,t} + y_{1,t+1} + \cdots + y_{1,t+n}\right)$$

$$yrp_{n,t} = \frac{1}{n}\left[E_t(h_{n,t+1} - y_{1,t+1}) + E_t(h_{n-1,t+2} - y_{1,t+2}) + \cdots + E_t(h_{2,t+n-1} - y_{1,t+n-1})\right]$$

$$yrp_{n,t} = \frac{1}{n}\left[E_t(xr_{n,t+1}) + E_t(xr_{n-1,t+2}) + \cdots + E_t(xr_{2,t+n-1})\right]$$

$$yrp_{n,t} = \frac{1}{n}\left[E_t(rrp_{n,t}) + E_t(rrp_{n-1,t+1}) + \cdots + E_t(rrp_{2,t+n})\right]$$

the mean of expected excess returns or the mean of expected future return risk premia, where $yrp_{n,t}$ denotes the yield risk premium on an n-term security at time t; $y_{n,t}$ is the spot yield for a n-period security at time t and $xr_{n,t}$ is the excess return on an n-period security at time t. $E_t(..)$ represents the expectations operator.

Chapter 3

A New *Preferred Habitat* Yield Curve Parameter

3.1 Introduction

Fixed income investors are concerned with the size of yields at various maturities and their associated term premia – the excess yields required to commit to holding long-term bonds instead of a series of shorter-term bonds (see Chapter 2 Appendix for definition). These result from the interaction of the supply and demand for maturity at each point on the yield curve and they can significantly influence its shape. I argue that the position of the term structure's traditional hump along the maturity axis contains new information that is not captured by the standard level, slope and curvature factors. For the *pure expectations hypothesis* (PEH) model, the maturity where curvature is greatest represents the time horizon where forward rates peak. In the more general case of varying term premia, this point may also reflect compensation for expected volatility and/or changing demands and supplies of bonds. Different investor types are known to favour different tenors (i.e. *preferred habitats* exist) and their preferences vary over time. Excess demands at any maturity will lower local term premia, assuming *limits to arbitrage*. Although attention is already paid to the size of these term premia (Adrian and Shin, 2010; D'Amico et al., 2011; Borio and Zhu, 2012), market participants rarely consider their pattern. Therefore, a key research question is whether the cross-sectional distribution of bond term premia by tenor can also help to explain macro-finance variables, such as future business activity, risk appetite and corporate credit spreads? Does a skew in these term premia towards a shorter average time horizon tell us something different from a distribution that is biased towards longer time horizons?

This chapter introduces a new yield curve parameter that helps to describe the distribution of term premia using a statistic, labelled D-star[10]. This characterises the lateral position of the traditional hump in the term structure of interest rates along the

[10] The 'D' in D-star relates to the distance of the hump along the maturity axis

maturity axis. Without actual term premia data and with reliable estimates not always available[11], for simplicity, I use spot yields to calculate D-star. D-star complements the traditional level, slope and curvature parameters, but it is also independent of them by construction, because standard measures of these other parameters net out from the calculation. Moreover, D-star contains no forward-bias because it is constructed using only current information. I argue below that the demand for maturity is a derived demand based on the desire for specific government bond duration and that imbalances between the supply and demand for maturity can explain changes in the position of D-star. Tables 1 and 2 and Figure 2 summarise my key estimation results.

Table 1: Cross-Correlation Coefficients between Yield Curve Factors, 1987-2016 (Monthly)

	Slope	Curvature	'Real' Term Premium	D-star
Slope	1.00			
Curvature	0.718	1.00		
'Real' Term Premium	0.647	0.664	1.00	
D-star	0.643	0.078	0.095	1.00

Sources: Federal Reserve, New York Federal Reserve and Adrian et al. (2014). Comment: The slope factor (10 year less 1 year yield) correlates closely with the other factors. Curvature correlates closely with the inflation-adjusted term premia, but has virtually no association with D-star. Equally, D-star seems unrelated to the level of the 'real' term premium. The 'real' term premium is the residual from a regression between the nominal term premium and US three-year trend inflation. It seems reasonable that D-star is not strongly related to either the size of the curvature parameter or the size of the term premium.

In practice, the interest rate term structure is more often characterised by its other parameters. The term structure is typically upward-sloping and concave to the maturity axis (see Gurkaynak, Sack and Wright, 2006). Curvature can be explained from the 'roll-down effect' as time elapses, where a 10-year bond, say, becomes a 9-year bond with a lower yield after 12 months (see Appendix A). Since the capital gains that derive from these yield falls are greatest at longer maturities, mid-duration bonds require a yield premium to equalise expected horizon returns [*duration effect*]. There may also be a yield premium (discount) caused by excess supply (demand) at different maturities

[11] The New York Federal Reserve and Gurkaynak, Sack and Wright (2006) publish estimates for the US Treasury market, but term premia are not always readily available and even in these cases they are estimated with sizeable errors and turn out to be highly collinear across maturities, with the largest premium often associated with the longest maturity.

[*preferred habitat effect*]. On top, greater interest rate uncertainty will boost the implied option value of longer-dated bonds [*uncertainty effect*][12]. This premium is linked to yield curve slope since extreme curve steepness can mean either short-dated yields rise and/ or long-dated yields fall, but in both cases higher yield volatility increases the size of this uncertainty effect.

Table 2: Cross-correlations (15 months ahead) and Granger Causality Tests (12 months) between US Financial Stress Index and High Yield Spread with various Yield Curve Factors, 1987-2016 (Monthly)

	Financial Stress Index	High Yield Spread
Slope	-0.479 (p=0.047,0.017)	-0.401 (p=0.059, 0.039)
Curvature	-0.339 (p=0.592,0.116)	-0.205 (p=0.383,0.000)
'Real' Term Premium	-0.212 (p=0.794,0.007)	-0.042 (p=0.011,0.043)
D-star	-0.539 (p=0.027,0.915)	-0.563 (p=0.020,0.981)

Comment: Both the financial stress index (using the first principal component of the published national FSIs) and the high yield spread (B less BBB-rated) show greatest correlation with D-star 15 months earlier. The slope factor demonstrates some influence. However, Granger causality tests demonstrate strong one-way causation for D-star in both cases and in the correct direction. This is not true of any of the other factors. The first p-value in brackets tests whether we can reject causation from each yield curve factor, and the second figure to the factor.

I argue that risk appetite is a key influence behind the demand for government bonds because US Treasury notes are the canonical safe assets for many investor types. Investors' demand for safety is often driven by a more uncertain and increasingly less favourable economic outlook beyond the investment time horizon characterised by D-star. Assuming that the position of the yield curve hump delineates regimes, a hump which occurs at a near-term maturity describes a less attractive approaching business outlook than a hump that occurs at a longer maturity. In the absence of full data on portfolio composition D-star also helps to identify the *preferred habitat* of investors through its connection to this safety dimension. The *preferred habitat* model of the term structure implies that the demand curve is relatively inelastic around the targeted time horizon. Shifts in these preferred habitats and short-term changes in the supply of bonds will together change prices and term premia at each specific tenor. I show below, in Section 3.3, that the greater the importance of a preferred habitat, the more movements

[12] Known by market participants as *convexity bias*. It operates through the square of duration. See Chapter 2 Appendix.

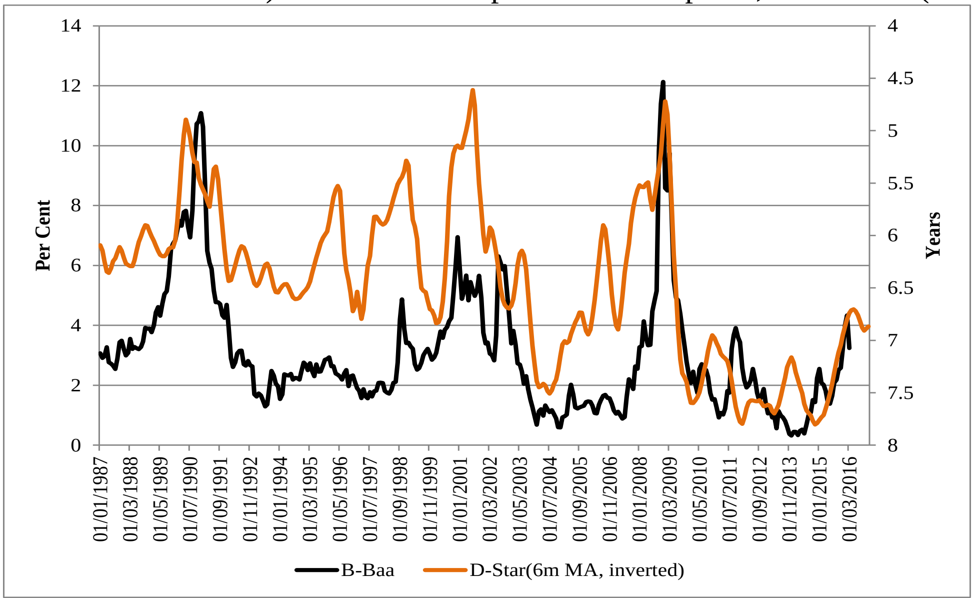
in supply will impact bond yields. Periods of excess demand (supply) for maturity will push yields at that tenor lower (higher). The position of the hump in the yield curve along the maturity axis (D-star) may therefore mark the boundary of the preferred habitat: in other words, beyond this horizon there is an excess demand for safe assets at all subsequent future maturities, less appetite for risk and lower Treasury term premia. Expansions and contractions in D-star tell us that the time horizon of investors is changing. These changes to investors' time horizons are transmitted through portfolio reallocations between risky and safe assets that result in, respective, excess demands and supplies. Longer investment horizons (larger D-star), therefore, may be associated with greater risk-seeking, more roundabout capital structures and, hence, higher productivity, faster business activity and lower credit risk. Similarly, vice versa.

Adding impetus to this search for more yield curve parameters, recent empirical studies increasingly question the validity of the conventional three-parameter decomposition, comprising level, slope and curvature (Cochrane and Piazzesi, 2005 and Adrian, Crump, Mills and Moench, 2014). Adrian, Crump, Mills and Moench, for example, replace the three-parameter yield curve model with a five-parameter alternative, justified following a Wald test on the rank of the factor matrix. The existence of D-star motivates an alternative yield curve decomposition. This new decomposition makes it easier to track down the influence of quantities on the shape of the term structure. It is, therefore, linked to the recent literatures on the effects of quantities on interest rates and on the supply of safe assets, such as government bonds, following LSAP[13]. A unique time-series of US D-star values that average 6.3 years (1946-2016), with a 10-month standard deviation, is derived and reported in Section 3.7 below. The results reported in Table 1 indicate the relationship between the standard factors and my estimates of D-star (see below). D-star is positively correlated with the yield curve slope (10-year less 1-year spread), but it is not strongly correlated with either the curvature (1-5-10 year butterfly spread[14]) or with the level of the Adrian et al. (2014) estimated 10-year nominal term premia, trend-adjusted for inflation to make it stationary. The more extensive[15] Gurkaynak, Sack and Wright (2006) term structure data also confirm that a high (low)

[13] Large-scale Asset Purchases (LSAP). Federal Reserve Balance Sheet rose 5 times to US$4.5 trillion from end-2007-16.
[14] The yield spread between a duration-matched 5-year *bullet* and a 1-year plus 10-year *barbell*
[15] The Adrian et al (2014) data contain cross-sectional annual tenors up to 10-years.

value of D-star is positively correlated (0.309) with a negative (positive) skew in the distribution of bond term premia. Table 2 shows the strong one-way Granger causality 15-months ahead between D-star and both the US high yield corporate bond spread (B-BBB[16]) and an index of US financial stress[17]. The close correlation between the future high yield spread and D-star is illustrated in Figure 2. A shorter horizon *preferred habitat* is implicitly linked to rising default risks over coming months because the B-BBB spread is a risk premia that is specifically associated with the incremental default probability of poorer quality corporate credits. D-star appears to one-way Granger cause movements in this spread around one-year ahead (p=0.020, 0.981): in comparison, the traditional yield curve slope (p=0.059, 0.039) and the Adrian et al. (2014) inflation-adjusted US Treasury 10-year term premia (p=0.011, 0.043) are far less effective predictors. It can be shown that 52% of the time over the sample period D-star moves oppositely to the direction of the average level of the US Treasury term premia.

Figure 2: D-Star (Position of Curvature Peak in Years, 6-month CMA, Advanced 15 months and Inverted) and B-BBB Corporate Credit Spread, 1987-2016 (Monthly)



Comment: The position of the curvature peak (D-star) advanced by 15 months and inverted predicts future movements in the US corporate high yield spread between single B and BBB bonds. The negative correlation between the two series is minus 0.563 and D-star is strongly one-way Granger causal.

When D-star is included alongside measures of the three standard yield curve parameters, the regression results compare favourably with the principal components

[16] The Moody's 'Baa' investment grade is equivalent to S&P's 'BBB' rating.
[17] This index is constructed from the first principal component of the various national US financial stress indexes (FSIs), backfilled to 1987 using their major subcomponents, e.g. corporate credit spreads and the CBOE VIX

decomposition. D-star contains additional information that, as I later show in Chapter 4, can help to predict a number of macro-finance variables besides those already mentioned, such as the ISM index of US business activity and popular measures of investors' risk appetite. D-star falls ahead of major recessions and predates periods of financial turmoil. For example, according to estimates derived from generic Treasury yield data, D-star dropped significantly from a local peak of 7.45 years in December 2005 to 4.41 years in September 2007 ahead of the 2007/08 Financial Crisis and Great Recession. It has since rebounded to a current reading of around 7 years. These forewarnings do not occur because fixed income investors are any more prescient or better informed than others, but because it is easier to extract forward-looking information from the Treasury yield curve. These signals also may be purer because government bonds are less distorted by other factors, such as illiquidity and default risk. Long-dated government bonds constitute safe assets for several key investors types and, therefore, the demand for bond duration is, at the same time, often a demand for safe assets at that horizon. This, in turn, reflects a corresponding fall in investors' overall risk appetite that will itself have future implications for the real economy.

This chapter is structured as follows: Section 3.2 reviews the recent preferred habitat and institutional finance literature. Section 3.3 examines the importance of duration management. In Section 3.5 I use the quadratic yield curve example to explain D-star, intuitively. Section 3.4 defines my measure of D-star. Section 3.6 describes the data and Section 3.7 provides monthly estimates for the position of the hump (D-star), using both security-level data from 1995-2016 and generic US Treasury spot yields over 1946-2016. Section 3.8 checks robustness. It compares the four parameter decomposition with principal components and estimates D-star directly from a Kalman filter technique. Section 3.9 concludes.

3.2 Review of the Preferred Habitat and Institutional Finance Literature

Term premia are assumed to be negligible under the *pure expectations hypothesis* (PEH), so rising interest rates rather than positive excess returns should follow periods of curve steepness (Fama and Bliss, 1987). Yet, it is well-documented (Ilmanen, 1995) that, in practice, three-month ahead excess returns *(ex post)* correlate with curve steepness (0.118). In addition, over the long-term when the mean-reverting behaviour of the yield curve washes out, the term structure still retains its concave shape. Thus, the return difference between a duration-matched *bullet* and *barbell*, i.e. the yield carry of a curve steepening strategy, earns an excess return, much like other examples of 'carry' in financial markets. Across four major bond markets – US, Germany, Japan and UK – the 1-5-10 year butterfly spread averaged +7bp (1986-2016) and +10bp (2000-16), showing that investors often pay premium prices for longer duration pay-offs. This contradicts the equality of horizon returns implicit in the PEH.

A mathematical analysis of these contributions (see Appendix A) shows how they can arise from: (1) the expectations of falling policy rates; (2) the excess demand for safe assets and (3) greater interest rate uncertainty. Each factor could be synonymous with sub-par future economic activity and a lower risk appetite among investors. These factors also affect the lateral position of the hump in the spot curve along the maturity axis. This position tells us the investment horizon where forward rates (and by implication expected policy rates) reach their maximum. This is explained (see Chapter 2 Appendix) because the duration-adjusted period change in spot yields is identically equal to the forward rate. When the hump occurs at shorter maturities, the economic outlook may be less favourable than normal and risk appetite low, while a hump positioned at an unusually long maturity could indicate risk-seeking behaviour and predate a future business cycle expansion. In cases where the PEH is superseded by the introduction of other factors into the pricing equation (e.g. the excess supply and demand for different maturities and/ or the option value of expected interest rate volatility), the position of the hump is also affected by the excess demand for safe assets and by the effects of greater interest rate uncertainty[18]. Ilmanen (1995) shows that, in

[18] This is derived mathematically in Appendix A

practice, excess supply and demand factors often dominate because the above *butterfly spread* measure of yield carry only shows a modestly positive correlation with *ex post* volatility (0.114).

The standard yield curve model is augmented to explain how these supply and demand factors influence US Treasury term premia. Tobin (1969) describes a *portfolio balance* mechanism that adjusts the overall quantity of duration, liquidity and credit risk in response to shocks to the relative supplies of money (the zero duration asset) and other securities. Additional frictions are introduced by the *preferred habitat hypothesis* (Modigliani and Sutch, 1966 and Vayanos and Vila, 2009) which opens up the possibility of market segmentation; through the importance of key investors in *institutional finance* models with non-standard stochastic discount functions for asset pricing (Adrian, Etula and Muir, 2010 and Haddad and Sraer, 2015) and with the existence of *limits to arbitrage* (Shleifer and Vishny, 1997). Modigliani and Sutch argue that bond interest rate risk should be measured relative to an investor's investment horizon, or *preferred habitat*, which vary by investor-type since different investors favour bonds of specific maturities. Investors' desire to avoid risk: *"...should lead them to hedge by staying in their maturity habitat, unless other maturities (longer or shorter) offer an expected premium sufficient to compensate for the risk and cost of moving out of [their] habitat."* (Modigliani and Sutch, 1966, p184). This means that yields are determined by the local supply and demand conditions at each maturity. Adjacent securities in the maturity structure are assumed to be imperfect substitutes, with the inelasticity of yields directly related to the distance away from the preferred habitat, which helps to justify term premia. According to the *preferred habitat* view, the preference of investor clienteles for specific maturities becomes a significant determinant of bond yields, when the maturity structure of government debt supply changes (Vayanos and Vila, 2009; Greenwood and Vayanos, 2009 & 2010; Guibaud et al. 2013).

The finance literature already recognises that this maturity dimension is important. The position of the hump on the spot curve is similar in concept to the maturity defined by the Fama (1986) peak forward rate, although he applied it to the money market curve. Fama's factor is also dependent on the level, slope and curvature of the term structure, and since it is expressed through forward rates it cannot define a unique point on the spot curve. The popular Nelson-Siegel-Svensson term structure model also contains a fourth parameter[19] that positions the hump and helps to determine the shape of the yield curve. Yet, this parameter is typically treated as a constant to expedite yield curve estimation despite strong evidence that it is time-varying. In other words, the tenor at which the curvature parameter is maximized plus the speed that the slope parameter decays are implicitly constant over time because they both only depend on this fixed 'shape' parameter. Koopman, Mallee and van der Wel (2007) and the published daily estimates by Gurkaynak, Sack and Wright (2006) for the US; by the Bundesbank (German data), and by the ECB (Eurozone data) all show that this fourth parameter changes significantly over time. Based on monthly reported estimates from 1980-2016 and acknowledging the potential identification issues, the German yield curve's tau_1 'shape' parameter has averaged 3.90, with a standard deviation of 4.40. According to daily estimates, the Eurozone yield curve's equivalent tau_1 parameter has averaged 3.92 since September 2004, with a standard deviation of 4.08. Similarly, the US tau_1 parameter has a mean of 2.39 and a standard deviation of 3.19, based on monthly data from 1961. Notwithstanding, Diebold and Li (2006) assume a constant 'shape' parameter that fixes the position of the Treasury yield curve hump at 2.5 years, while Diebold et al. (2006) state that this 'shape' parameter has: *"... no obvious economic interpretation."* (p3). In contrast, Fama (1986) uses information from the position of the hump to derive an alpha-generating strategy for the money market curve. He selects the maturity where the forward rate is highest because that maximises the roll-down returns from a portfolio, given that the forward rate defines the duration-adjusted change in the spot rate between two maturities.

Adrian, Etula and Muir (2010), Domanski, Shin and Sushko (2015) and Haddad and Sraer (2015) all demonstrate the importance of specific financial intermediaries for asset pricing. Domanski, Shin and Sushko study the insurance sector and note that European companies consciously run wide duration gaps between their assets and liabilities of 5-10 years. They show empirically that a greater net demand for duration leads to lower government bond yields and they conclude that a 'hunt for duration' among risk averse investors may often dominate the traditional search for yield, notably though an amplification mechanism when yields themselves are falling. Leibowitz, Bova and

[19] Traditionally termed tau, or tau_1 when a fifth parameter tau_2 is included.

Kogelman (2014), argue that *duration targeting* drives the portfolio rebalancing of institutional bond and bond mutual funds. Greenwood, Hanson and Stein (2010) confirm this for corporate financial managers. They also argue that corporations have more flexibility over issuance, although, in practice, Treasury debt managers look to do the same.

3.3 Duration Management and the Demand and Supply for Maturity

This section extends the *preferred habitat hypothesis* to asset duration and considers the effects of imbalances between the supply and derived demand for maturity on the shape of the yield curve. Bonds are supplied at certain maturities, but are demanded, in part, for their durations. Duration, which is defined in Chapter 2, is widely-used as a portfolio target by many investors. It follows that the demand for specific maturities is a derived demand. However, actual data on the maturity structure of asset holdings by investor type are hard to find. Recent investor surveys by *Asset International* show the evolution of liability duration and fixed-income portfolio duration across a sample of major US pension funds. Only six years of data exist, but they appear to be consistent with these observations, showing broadly stable levels of liability duration of around 14 years; positive co-movements between asset and liability duration, and a duration gap between fixed-income assets and liabilities that averages 2-3 years. See Figure 3.

Therefore, in practice, many long-term funds are concerned with the duration of their liabilities as well as the volatility of their assets. This opens up the possibility that the aggregate supplies of bonds at certain maturities may not align with these aggregate demands derived from duration targets. Not surprisingly, recent LSAP policies have focussed more attention on potential imbalances between the supply and demand for maturity. Prior to the 2007/08 Global Financial Crisis (GFC), Reinhart and Sack (2000) found bond yields to be negatively related to the size of the fiscal surplus. The period since the GFC has seen significant increases in Treasury issuance (+105%, 2008-16) and in the size of holdings of Treasury securities on the US Federal Reserve’s balance sheet (+330%, 2008-16) as part of LSAP policies. In addition, there have also been deliberate attempts by policy-makers to target an increase in the average maturity of outstanding debt. According to official data, the average maturity of the stock of US Treasuries reveals significant variation over time, as shown in Figure 4. Average debt maturity fell from a peak of 10.35 years at end-1946 to a low of 2.41 years at end-1975, and currently stands at 5.74 years (end-2016). The duration of the *Thomson Reuters* US government bond index shows similar movements (correlation 0.759) and in the 2008-12 period that characterised LSAP it rose from 4.66 to 11.03 years. Using monthly data since year 2000, increases in the proportion of US Treasuries supplied in the 5-10 year maturity band positively correlate (0.55) with higher relative yields, as measured by the spread between 10-year bonds and an average of 5-and 20-year bonds. Greenwood, Hanson and Stein (2016) argue that supply shortages at the front-end of the money market curve, measured by the ratio of outstanding Treasury bills to GDP, depress bill rates disproportionately. Greenwood and Vayanos (2009) find that falls in the value of maturity-weighted debt to GDP lower long-term yields. Similar results can be found in UK gilt data and for Japan (Iwata and Fueda-Samikawa, 2013).

Alongside this jump in the volume of Treasury issuance, the LSAP enacted following the GFC and, in particular, the Federal Reserve's Maturity Extension Programme (MEP), or so-called Operation Twist 2 policy[20], explicitly attempted to alter the term structure of US interest rates via a duration channel. By substantially raising the average maturity of their US Treasury SOMA holdings[21] towards a target of 10 years[22] policy-makers sought to push down longer-term interest rates and so deliver a boost to the sluggish American economy. Gagnon (2016) summarises recent empirical studies to show that a 50bp fall in 10-year Treasury yields is the median response to a LSAP equivalent to 10% of GDP. Krishnamurthy and Vissing-Jorgensen (2012) find that the announcement effect of the MEP lowered US 30-year yields by some 40bp and raised 3-year yields by around 10bp. D'Amico et al. (2012) suggest each one-year decline in average Treasury maturity pushes down medium duration US yields by 100bp. Chada (2014) shows a like-sized effect of 120-180bp for long-term yields. The near-two year

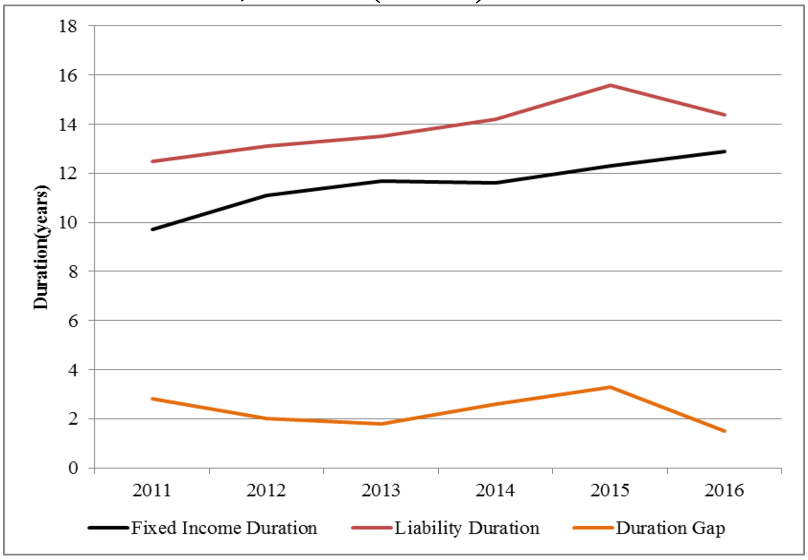
[20] Operation Twist 2 was instituted in two parts. The first ran from September 2011 through June of 2012, and involved the redeployment of $400 billion in Fed assets. The second ran from July 2012 through December 2012, and encompassed a total of $267 billion. Operation Twist 1 occurred in 1961: Fed estimates suggest it lowered long-yields by a small 14bp

[21] System Open Market Account (SOMA)

[22] On average through 2005 SOMA maturities averaged around 4.56 years. LSAP1 (11/25/2008 to 3/31/2010) raised this to 6.6 years; LSAP2 (11/3/2010 to 6/30/2011) maintained this at 6.13 years and LSAP3 (9/13/2012 to 12/18/2013) pushed this out to 8.03 years. The LSAP is more popularly known by the QE acronym.

fall in average US Treasury maturity between 2001 and 2009 could, therefore, explain as much as 300bp of the decline in US long-term Treasury yields over the period.

Figure 3: Liability Duration and Fixed Income Portfolio Duration – Sample of Major US Pension Funds, 2011-16 (Annual)



Source: Asset International; Comment: Six years of annual survey data for a sample of major US pension schemes appear to show co-movement between average fixed income asset duration and liability duration, with the latter around 2-3 years higher.

Vayanos and Vila (2009) and Greenwood and Vayanos (2009) show the conditions necessary for these supply and demand imbalances to be arbitraged away. Greenwood, Hanson and Stein (2010) build on this work, using a 'gap-filling' model of corporate debt issuance to show how these imbalances also affect quantities in the long-term. Their model is adapted in equation (3) to demonstrate the theoretical effect of supply and demand imbalances in pushing Treasury yields at any maturity away from a PEH benchmark. The model assumes: (1) partially segmented markets, featuring preferred habitat investors, such as pension funds that demand long-term assets; (2) Treasury supply shocks that are large relative to the supply of arbitrage capital, and (3) risk-averse and capital-constrained arbitrageurs, such as hedge funds[23], that attempt to enforce the expectations hypothesis as best they can. These arbitrageurs incorporate short-term interest rate expectations into bond prices and bring bond yields into line with each other by buying and selling across the different maturities and smoothing local supply and demand pressures, thereby enforcing an arbitrage-free term structure.

[23] The capital of Fixed Income (US$684 billion) and Global Macro (US$511 billion) hedge funds exceeded US$1 trillion in 2014, equivalent to around 7% of outstanding bonds. Source: *Hedge Fund Research*.

They demand higher bond term premia as their exposure to duration increases because they are risk-averse. Without these arbitrageurs, each bond tenor would constitute a separate market, with its yield determined by the investor cohort for that specific maturity. Factors that cause supply and demand imbalances; uncertainty, and factors that alter the strength of arbitrage activity will raise the term premium on long-term government bonds of *m* years maturity and so affect the shape of the yield curve across each tenor, resulting in a term structure that could be increasing, decreasing, humped, or even of an irregular shape. An excess supply (demand) denoted by $G_m > L_m$ ($G_m < L_m$) drives yields at each maturity, *m*, higher (lower):

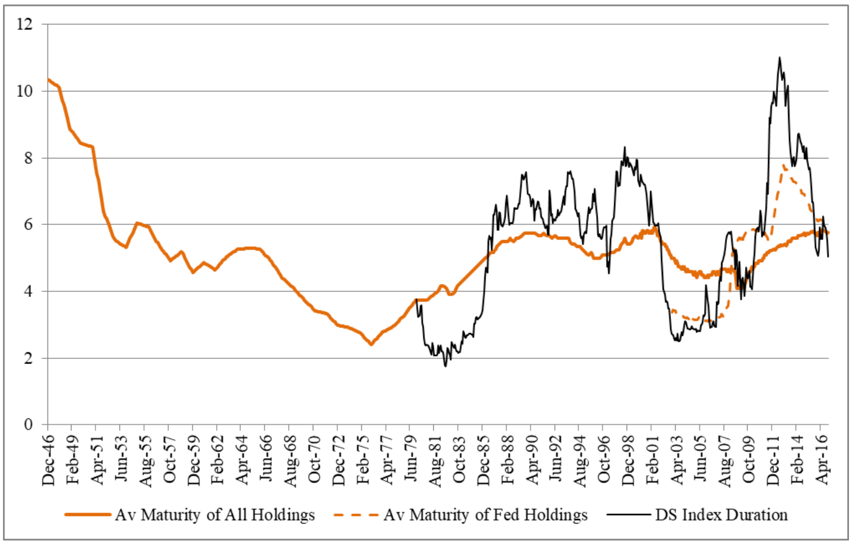
$$P_m^{*-1} - (1 + r_1)(1 + E[y_m]) = \frac{(1 + r_1)^2 Var[y_m]}{\gamma}(G_m - L_m) \qquad (3)$$

where r_1 represents short-term interest rates in period one and y_m denotes spot yields over the periods two to *m*. r_1 is known and y_m randomly distributed with mean $E[y_m]$ and variance $Var[y_m]$; P_m^* denotes the market-clearing default-free bond price at maturity *m*; γ is the risk tolerance of arbitrageurs, $\gamma > 0$; G_m is long-term government bond issuance and L_m is the demand for long-term bonds of maturity *m* by preferred habitat investors.

Imbalances can arise from both investor demand (L_m) and/ or from government supply (G_m) for any of three reasons: (1) over-issuance of a specific maturity (G_m), net of any LSAP, and low demand (L_m) for that tenor, in turn, because of (2) liability duration and/ or (3) investors' *risk appetite*[24]. From equation (3), a rise in average Treasury maturity increases G_m at longer maturities, pushes up term premia and so lengthens D-star. In turn, an increase in D-star, independent of the supply of maturity, indicates less excess demand for long maturity bonds, i.e. a fall in L_m. This increases term premia around and beyond the maturity *m*.

[24] According to Gai and Vause (2006), *risk aversion* is a characteristic of underlying utility functions, whereas *risk appetite* results from the interaction between risk aversion and the macro-economic background.

Figure 4: The Average Maturity of US Treasury Securities Outstanding, 1946-2016; the Average Maturity of Federal Reserve Holdings, 2003-16 and Duration of Aggregate US Treasury Bond Index, 1980-16 (Years, Monthly)



Source: US Treasury, Federal Reserve, Thomson Reuters; Comment: The average maturity of the outstanding stock of US Treasuries show significant variation over time. It reached a low in the high inflation, mid-1970s and is currently close to a 65-year peak. Duration of the *Thomson Reuters* US Treasury bond index has already peaked. (The series have a 0.759 correlation coefficient). The average maturity of US Federal Reserve Treasury holdings is also shown. Taking into account their recent jump, this points to a lesser rise in the effective maturity of outstanding Treasuries held by the private sector

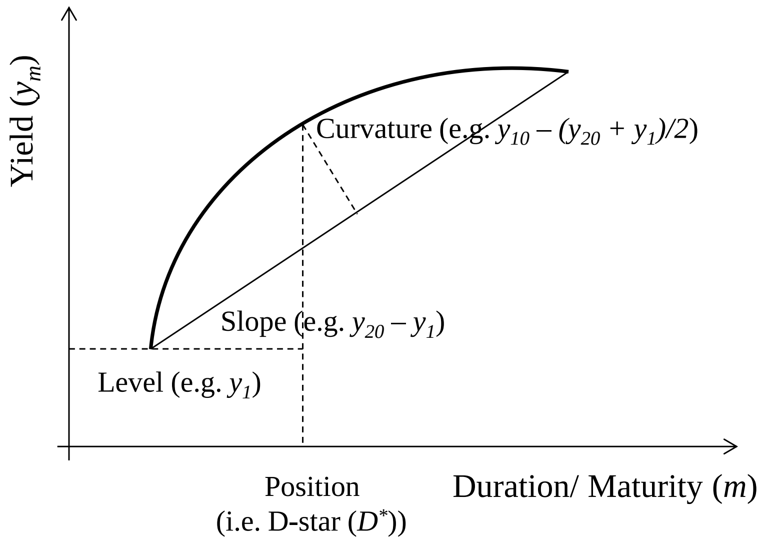
This *preferred habitat* model reduces to the *pure expectations hypothesis* (PEH) when the right-hand side of equation (3) is zero. This requires that: (a) the supply and demand imbalances do not persist, such that government supplies of long-term bonds match preferred habitat demand ($G_m - L_m = 0$); (b) arbitrageurs face no interest rate risk ($Var[y_m] = 0$), and/ or (c) there is non-strict market segmentation, allowing sufficient buyers and sellers of bonds flexibility to alter their investment horizons and so arbitrage away anomalies. In theory, this requires that γ is infinitely large, so that arbitrageurs are risk-neutral. In practice, rather than extreme segmentation, it is more likely that the active arbitrageurs transmit local shocks on to nearby maturities, subject to their risk tolerance and their access to funding. These latter two factors probably fluctuate over time, thereby raising and lowering the intensity of arbitrage activity (γ). For example, business cycle and monetary policy shocks may reduce arbitrageurs' risk appetite and limit arbitrage, so amplifying the effect of any imbalances and suggesting that preferred habitat models are well-suited to turbulent times (Strohsal, 2013). Equally, abundant liquidity may permit an increase in arbitrage that drives up their risk tolerance parameter (γ) thereby reducing the impact of any quantitative imbalance on prices.

From equation (3), term premia will also vary positively by maturity according to the degree of yield volatility ($Var[y_m]$). Volatility, in turn, is affected both by changes in the riskiness of investments and by fluctuations in general investors' *risk appetite* (Gai and Vause, 2006). Cieslak and Povala (2014) among others note that the term structure of yield volatility has lately flattened. For example, since end-2007, the annualised monthly volatility of one-year US Treasury yields has averaged 1.95%; five-year, 2.32%; 10-year, 2.48% and 20-year, 2.75%. Prior to 2008 yield volatility across the term structure averaged 10.16%, compared to 2.16% since. Applying this fact to equation (3), it follows that changes in the distribution of term premia will largely depend upon the excess supply and demand for maturity. However, fluctuations up and down in the level of the volatility term structure and changes in the intensity of arbitrage activity can both still affect the average size of bond term premia across the yield curve. During such times, changes in the term structure of term premia, as measured by D-star, give a truer measure of the excess supply and demand for maturity and general investors' *risk appetite* than the level of term premia. This provides a rationale for its calculation and may also explain why D-star has a low correlation with the level of term premia.

3.4 An Intuitive Explanation of D-star Using the Quadratic Yield Curve

What is going on may be better understood from the quadratic yield curve. Here, the single hump is symmetric and its position can be unambiguously measured by its point of peak curvature along the maturity axis. As illustrated in Figure 5, D-star (D_t^*) coincides with the maturity of the largest absolute perpendicular distance between different points along the yield curve and the average slope between a short-term bond (e.g. one year) and a very long-term bond (e.g. 20 years). In the special case of the quadratic, D-star is directly related through differentiation to the ratio between the slope parameter and the curvature parameter of the yield curve. When these two other parameters move together (1946-2016 correlation between curvature and slope is positive 0.786), the position of peak curvature is unaffected. Larger proportionate movements in the slope extend the position of the curvature peak further along the maturity axis. It follows that a steepening curve with unchanged curvature has a curvature peak at ever-lengthening horizons. Abstracting for a moment from the effects of excess demand, the yield curve slope indicates the trend in interest rates, while the degree of curvature implies the likelihood of future mean-reversion in rates and/ or interest rate uncertainty. Hence, a steeply-sloped, near-linear yield curve suggests that interest rates move to a permanently higher level, consistent with a stronger economy. Equally, a flat, bulging yield curve suggests persistent cyclicality in both interest rates and in the real economy. Intuitively, D-star should take the larger value in the former case. In the case of the quadratic it does, because a high (low) slope to curvature ratio corresponds to a high (low) D-star value.

Figure 5: Yield Curve – Level, Slope, Curvature and Position



Comment: Schematic breakdown of term structure into four parameters: level, slope curvature and position

This new parameter helps to explain why some market participants read steep yield curves with less curvature favourably – indicating future economic strength, and flat, bulging curves unfavourably – as future economic warning signs. Consider three examples: (i) between 1996-97 and again through 2011-12 the US Treasury yield curve slope flattened significantly, but since its curvature dropped *pari passu* there were no recession warnings; (ii) the slope was also below average throughout most of the 1961-70 decade, but confirmation of the coming 1970 recession required the rise in curvature in 1969, and similarly (iii) the drop in slope through 2005-07 only constituted a recession warning when curvature failed to match the drop and actually rose in 2007.

D-star is therefore related to yield curve slope movements, conditional on non-matching moves in curvature. In general, thinking of D-star as a non-linear transformation of the slope, where the non-linearity is driven by the curvature, links it to the evidence given by Moench (2012), who shows that curvature has predictive content for the business cycle. Other papers emphasise the slope (see Estrella and Hardouvelis, 1991): both are partly right, but confusion comes from the non-linear link between slope and curvature. Paradoxically, D-star alters most when the paths of the slope and curvature diverge, rather than when they move together.

In summary, there is information contained in the yield curve slope; information in the curvature of the term structure and information in their non-linear combination, which for the quadratic describe the positions of the curvature peak and D-star. In cases other than the quadratic function, such as non-parametric yield curves, the position of the curvature peak is harder to calculate from analytical methods and may have less meaning. I, therefore, propose a general estimation method to identify the position of the hump. This weighted-average of standard geometric distance measures is derived in the next section. Its calculation is straightforward; independent of the method of yield curve estimation, yet specific to each term structure.

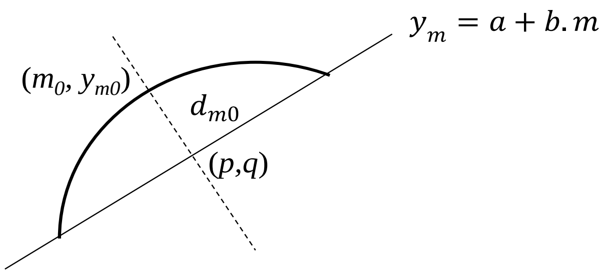
3.5 D-star: Measuring the Position of the Yield Curve Hump

This section describes a general, non-parametric measure for the lateral position (m_0) of the hump in the term structure that is independent of the mathematical formulation used to generate the yield curve. It uses a standard geometric measure of the perpendicular distance (d_{m0}) from a point (m_0, y_{m0}) to a line, as defined by:

$$y_m = a + b.m$$

where m denotes maturity and y_m is the spot yield for that maturity. Let the perpendicular intersect the line at another point (p, q). Then, the distance d_{m0} between these points is:

$$d_{m0} = \sqrt{(p - m_0)^2 + (y_{m0} - q)^2}$$



The values of m_0, y_{m0}, a and b are known. Squaring both sides and multiplying by (b^2+1) to eliminate the two unknown values p and q, gives:

$$(b^2 + 1)[(p - m_0)^2 + (y_{m0} - q)^2] =$$

$$(p - m_0)^2 - 2b(y_{m0} - q)(p - m_0) + b^2(y_{m0} - q)^2 +$$

$$b^2(p - m_0)^2 + 2b(y_{m0} - q)(p - m_0) + (y_{m0} - q)^2$$

$$(b^2 + 1)d_{m0}^2 = [b(p - m_0) + (y_{m0} - q)]^2 + [(p - m_0) - b(y_{m0} - q)]^2$$

And since if follows that $q = a + bp$ and $b = (p - m_0)/(y_{m0} - q)$, this can be rewritten as:

$$= (y_{m0} - a - bm_0)^2 + 0$$

Therefore, dividing both sides by (b^2+1) defines an expression for distance at each tenor:

$$d_{m0}^2 = \frac{(y_{m0} - a \ - bm_0)^2}{(b^2 + 1)}$$

Or, taking the square root and re-expressing in absolute terms:

$$d_{m0} = \frac{|y_{m0} - a \ - bm_0|}{\sqrt{(b^2 + 1)}}$$

At each point in time (t), there exist distance measures for each maturity $m = 0,\ldots,n$. The distance-weighted average of these maturities[25] describes the position of the hump (D_t^*):

$$D_t^* = \frac{\int_{m=0}^{n} m \cdot d_{m,t}}{\int_{m=0}^{n} d_{m,t}} = \int_{m=0}^{n} w_{m,t} \cdot m$$

where $w_{m,t} = d_{m,t}/\int d_{m,t}$ is the weighting factor for each tenor, m

This expression describes the maturity of the average curvature and defines D-star (D_t^*). The expression is positive by definition because maturity (m) exceeds zero and the weights used to calculate the average comprise individual distances ($d_{m,t}$) measured in absolute terms. It can be calculated for different shaped interest rate term structures, including multiple-humps, convex humps, inverted and partially-inverted structures. D-star can be defined in the case of an inverted term structure because absolute distance measures are used. Equally, the aggregation of these distance measures over the cross-section of maturities means that D-star can be calculated for term structures with multiple humps. It may or may not coincide with the point of peak curvature along the maturity axis, which is defined as the horizon (m) with the greatest distance measure ($d_{m,t}$). When curvature is symmetric with a single hump, these measures should align,

[25] Market participants might describe this as the 'duration-weighted average butterfly spread across tenors'.

but when curvature is positively (negatively) skewed the average maturity reading will lie above (below) the peak curvature.

In practice, like the similar measures of level (e.g. $y_{1,t}$), slope (e.g. $y_{10,t} - y_{1,t}$) and curvature (e.g. $y_{5,t} - (y_{10,t} + y_{1,t})/2$), the value of D-star depends upon which bond maturities are included in the calculation. Correspondingly, it is inappropriate to compare a D-star value calculated over a maturity range of 20-years with one measured over 10-years. Another issue is continuity. Bonds are often issued at specific maturities (and generic US Treasury yields are published at 1, 2, 3, 5, 7, 10, 20 and 30 years), which means that this statistic will take discrete and possibly non-unique values at each sampling point. Therefore, in order to estimate D-star, I approximate it using the discrete time horizons $m = 1,\ldots,n,$ for each monthly data point as:

$$D_t^* \approx \frac{\sum_{m=1}^{n} m \cdot d_{m,t}}{\sum_{m=1}^{n} d_{m,t}} \qquad (4)$$

where $m = 1,\ldots.,n$, $d_{m,t} \geq 0$, for all m.

3.6 Data Description

I test two different data sets. First, I take the redemption yields and Macaulay durations of all extant US Treasury securities[26]. The prices, coupons and other features of these bonds were down-loaded from Bloomberg for each month-end, starting in January, 1989. Securities with call features and all securities with durations below one-year were eliminated from the sample to avoid liquidity and negative yield questions. The Bloomberg data is less populated in its early years, because securities that were issued prior to the electronic platform’s start date in 1989 are not included. Thus, a 20-year bond issued in, say, 1988 is not logged by the database. Consequently, I mainly rely on data from January, 2000 onwards, which is the date from when there is a minimum sample size of at least 110 securities and from where the traditional level, slope and curvature parameters of the overall yield curve more closely align with the generic

[26] It is conventional to construct a security-level yield curve using duration not maturity.

counterparts calculated by the Federal Reserve. Over the 2000-2016 period, the sample contains an average of 167 Treasury securities for each month. Appendix B provides the data for 30th December 2012.

In order to lengthen the sample span before 2000, this security-level data is complemented by generic spot yield data for US Treasury notes and bonds of 1-,2-,3-,5-,7-,10- and 20-year constant maturities, all sourced from the US Treasury and published in the Federal Reserve's H15 release. These monthly data, chosen for their long history, are calculated as the average of nominal daily yields and they begin in April 1953, although 2-year notes only start from June 1976. To further increase the sample size, I also take zero coupon US Treasury yields covering the earlier[27] period 1946-1953 from Shiller (1990) and splice these on to the official US Treasury series. The data sample extends through to December 2016. The US Treasury, in addition, publishes yield data for 30-year bonds starting from February 1977. However, the 30-year bond is typically less liquid than some of the earlier maturities, such as the 10-year note, and between March 2002 and January 2006 new issuance of 30-year bonds halted altogether[28]. This creates potential estimation problems because the 30-year is only available for roughly half the entire data period. In addition, the typical yield curve flattens noticeably beyond the 15-20 year maturities, which makes calculating a consistent statistic difficult. Consequently, I consider maturities that terminate with the 20-year Treasury note.

These officially published daily generic yields are themselves interpolated by the US Treasury from a fitted yield curve of actual issued bonds, using a spline-based model described in BIS (2005) and summarised in Appendix D. These latest mathematical techniques involve the fitting of piecewise polynomial splines to different parts of the coupon curve, that, in turn, ensure continuity and smooth joins. The resulting bootstrapped forward curves are then used to consistently interpolate zero coupon bond yields at specific maturities. Since the yield curve data are calculated for zero coupon bond equivalents, maturity (M_t) and duration (D_t) are identical, i.e. $D_{1,t}=M_{1,t}=1$; $D_{2,t}=M_{2,t}=2$, etc. There are two alternative choices of dataset: (1) Gurkaynak, Sack and

[27] The Third Liberty Bond Act, passed at the end of WW1, set a yield ceiling of 4¼% on all new issues of longer than seven years maturity, and until the 1951 Accord, the Fed was *de facto* under US Treasury control and expected to maintain a 2½% Treasury yield ceiling.

[28] Traditionally, US Treasury bond maturities between 11-29 years are considered the least liquid.

Wright (2006) report the Federal Reserve's own internal estimates, starting from 1981 and based on a fitted Nelson-Siegel-Svensson curve that interpolates between the standard maturities from one to 20-years. And (2) the Fama-Bliss CRSP, which creates zero coupon yields at fixed maturities up to 5-years using unsmoothed forward rates. In practice, the differences between these yields and the US Treasury's own calculations are moderate-to-small, averaging 14bp across the curve with an average 14bp standard deviation at each maturity, or some 1.8%.

The US Treasury also publishes data on the average[29] maturity of the outstanding stock of Treasury securities. Similar data on the average maturity of Federal Reserve Treasury holdings can be calculated from the published breakdown of Treasury holdings in the SOMA by broad maturity. I use these estimates to adjust the published Treasury series in order to estimate the effective supply of maturity to the private sector.

3.7 Estimation of D-star

I apply the curvature position measure (D-star) in equation (4) from Section 3.5, which defines the maturity of the average curvature at each cross-section, to the two US Treasury data sets described in Section 3.6. As a cross-check, I also calculate the point on the maturity axis where the curvature peaks (D-peak). As expected, this turns out to be a jumpy time series because it can only take discrete values (e.g. 1, 2, 3, 5, 7, 10 and 20 years for the generic Treasury data).

Table 3: Summary Statistics – Various Estimates D-Star, 1946-2016 (Monthly)

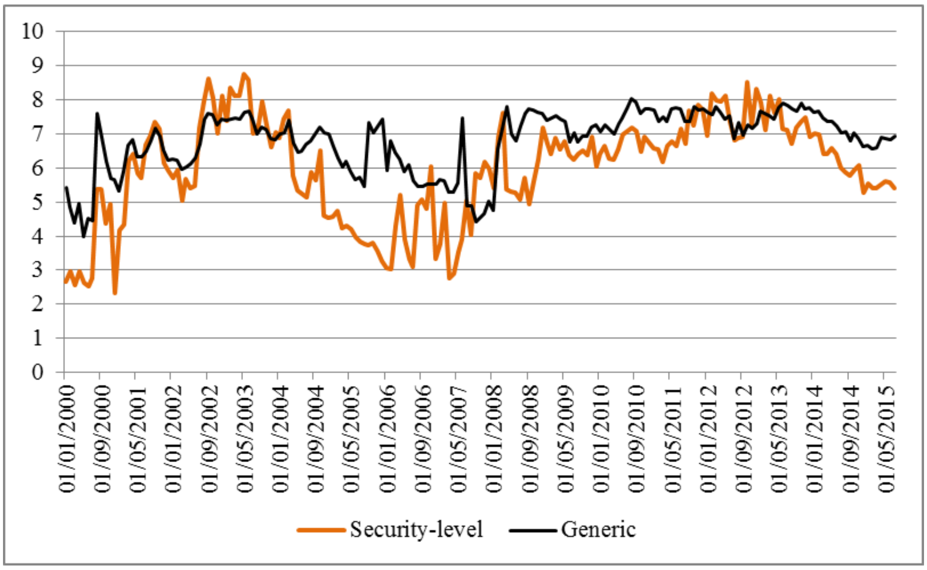
	Mean	Mean (CS)	StdDev	Min	Max	Sample
D-star$_g$	6.27	6.48	0.84	3.35	8.40	1946-2016
D-star$_s$	5.46	5.46	1.64	2.32	8.75	1989-2016
D-peak$_g$	6.53	6.80	2.37	1.00	10.00	1946-2016
D-peak$_s$	4.97	4.96	3.29	0.03	10.93	1989-2016

The subscripts g and s refer, respectively, to the generic Treasury and security-level data sets. D-star is the maturity or Macaulay duration of the average curvature. D-peak is the maturity or Macaulay duration of the peak curvature. CS denotes common sample. StdDev is the standard deviation. Comment: the means of the generic Treasury and security-level coupon data appear to be close.

[29] I acknowledge that the mean is an inappropriate measure when there are perpetuities. Here, the median (or duration) would provide a less ambiguous estimate of the 'age' of the outstanding Treasury stock.

Appendix B reports the underlying calculations behind D-star for the US Treasury term structure as of 30th December 2012, based on all 265 outstanding US Treasury coupon-paying securities. On this date, D-peak is measured as 10.22 years and D-star as 8.26 years. Note that the generic and security-level data are not strictly comparable. The generic data implicitly assumes an equal number of securities available at each maturity and so it is unaffected by differences in the distribution of issuance. Thus, the average Macaulay duration of the generic yield data is a constant 6.86 years and 4.87 years (30th December, 2012) for the individual security data. Like the traditional level, slope and curvature parameters, the D-star measures are specific to each data set.

Figure 6: Maturity of Average Curvature (D-star) – Security-level and Generic US Treasury Yields, 2000-2016 (Monthly, Years)



Source: Author's calculations; Comment: The chart reports estimates of D-star – the average position of the hump in years along the maturity axis – for the security-level and generic Treasury data. The two series show correlation of 0.708, although I acknowledge they are not strictly comparable. Macaulay duration replaces maturity for the security-level data.

Table 3 reports the means and dispersion for the two D-star and D-peak measures. Figure 6 compares the D-star values for the generic yield data and the security-level data since year 2000. The common-sample average values of D-star for the generic Treasury curve (6.48) and the security-level data (5.46) look similar and, according to Table 4, they correlate closely (0.529). The monthly estimates of D-star and D-peak for the generic Treasury data (0.751) and security level data (0.858) are also highly correlated. I will focus on D-star and favour the generic Treasury data largely because, unlike the security-level data, they are unaffected by changes in the distribution of outstanding bonds at each maturity and they provide a much longer time-series spanning nearly 70 years. Since my aim is to measure the effect of changes in the distribution of maturity on the shape of the curve, the raw security-level data would be inappropriate without the sample being stratified.

Table 4: Correlation Coefficients –Estimates D-Star and D-Peak, 1989-2016 (Monthly, Common Samples)

	D-star$_g$	D-star$_s$	D-peak$_g$	D-peak$_s$
D-star$_g$	1.000			
D-star$_s$	0.529	1.000		
D-peak$_g$	0.751	0.403	1.00	
D-peak$_s$	0.610	0.858	0.508	1.00

The subscripts g and s refer respectively to the generic Treasury and security-level data sets. D-peak is the maturity or Macaulay duration of the peak curvature. D-star is the maturity or Macaulay duration of the average curvature. Comment: D-peak and the D-star appear to correlate closely for both datasets.

For the generic Treasury data, Table 3 shows that over 1946-2016 D-star averages 6.27 years, with a 0.84 year (10 month) standard deviation and a range of 3.4 to 8.4 years. The data are stationary at the 1% level according to adjusted Dickey-Fuller tests, and persistent, with a positive 0.769 autocorrelation coefficient on the preceding month. They have a negative skew and exhibit non-normality according to a Jarque-Bera test. Figures 7 and 8 show, respectively, that D-star has a high positive correlation with the yield curve slope (0.577) and a more modest positive correlation with curvature (0.142). From the charts, D-star (6-month centred moving average) appears to frequently move independently of each parameter. Yet, a multiple regression of D-star on the slope and curvature parameters gives a high R-squared (0.601), with a positive loading on the slope parameter and a negative loading on curvature (consistent with the earlier 'quadratic' interpretation) and with both being significant at the 1% level (using Newey-West adjusted standard errors). D-star rises fastest when the slope increases and curvature falls. Thus, upward-sloping, linear yield curves are associated with large D-star values, and flat, bulging yield curves align with low D-star readings. This can also be seen from Table 5, which pigeon-holes the data into each of three groupings, depending on whether slope and curvature are within or outside one-half standard deviation of their period means. Term structures with steep, linear slopes on average have the highest D-star readings (7.48), whereas flatter and bulging yield curves have lower readings. This seems plausible because, as noted in Section 3.5 above, a near-linear, upward-sloping spot curve implies that forward rates rise to a new, permanently-higher level. In contrast, a flat, bulging curve is consistent with more cyclicality and a high degree of uncertainty about future interest rates.

Table 5: US Treasury Yield Curve Classified by Slope, Curvature and D-star, 1946-2017 (Monthly)

		Slope	
	High	*Average*	*Low*
High	17.9% 6.54 years	6.9% 5.92 years	0.0% N/A
Curvature *Average*	6.3% 7.29 years	27.5% 6.16 years	10.7% 5.65 years
Low	2.0% 7.48 years	7.6% 7.15 years	21.1% 6.39 years

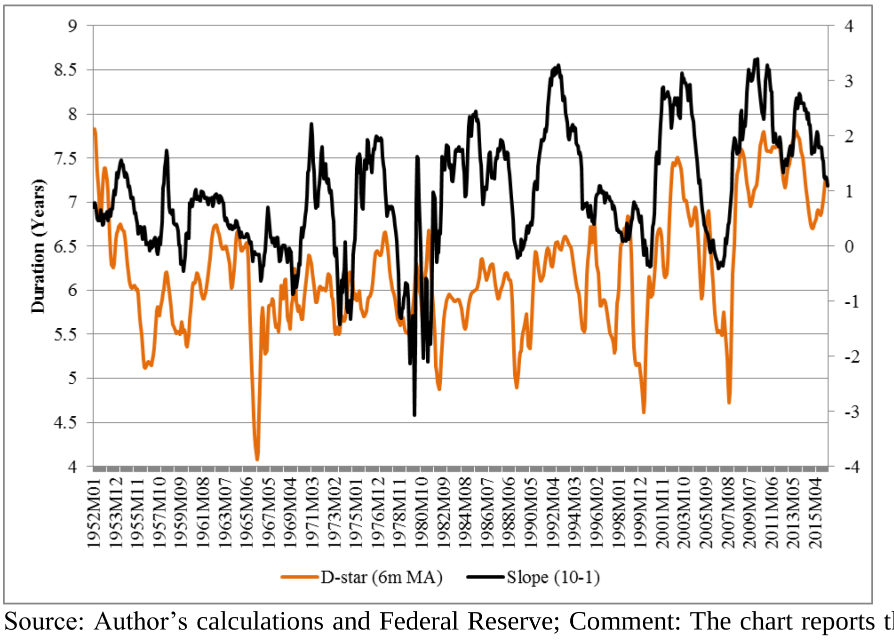
The sample is segmented into two sets of three buckets by slope (10 year less 1 year yield) and curvature (1-5-10 year butterfly spread), according to whether the parameter values were above('high'), below ('low') or within ('average') one-half standard deviation of the period mean. The upper number in the table refers to the percentage of the sample data in that category. The lower number refers to the average D-star value. The data show that D-star consistently rises as the slope steepens and as the curvature falls.

As a robustness check, the distribution of estimated Treasury term premia[30] is negatively (positively) skewed (correlation coefficient 0.309) when the value of D-star is high (low). D-star also correlates positively with the yield difference between the 1-2-3 and 7-10-20 year butterfly spreads (0.562). This should approximate a more distant yield curve hump because it identifies greater curvature at longer horizons. Moreover, this correlation grows tighter over time (0.694, 1990-2016) and, noticeably so since the 2007/08 Financial Crisis (0.763, 2009-2016). According to equation (2), increases in the supply of long-dated Treasuries raise risk premia at longer maturities as these safe assets become more abundant, and because investors in general take-on more duration risk (Krishnamurthy and Vissing-Jorgensen, 2011). D-star includes the effects of supply. Published supply data on the average maturity of outstanding US Treasury bonds (see Figure 4) reveal a long-run positive correlation with D-star (0.381). This is consistent with an upward-sloping demand curve for maturity (versus yields) and an

[30] Gurkaynak, Sack and Wright (2006) term structure data

assumption that issuers tend to be opportunistic and relatively unconstrained in the maturities they choose to supply over the long-term.

Figure 7: D-star (6-month CMA) and Yield Curve Slope (10-1 year), 1946-2016 (Monthly)



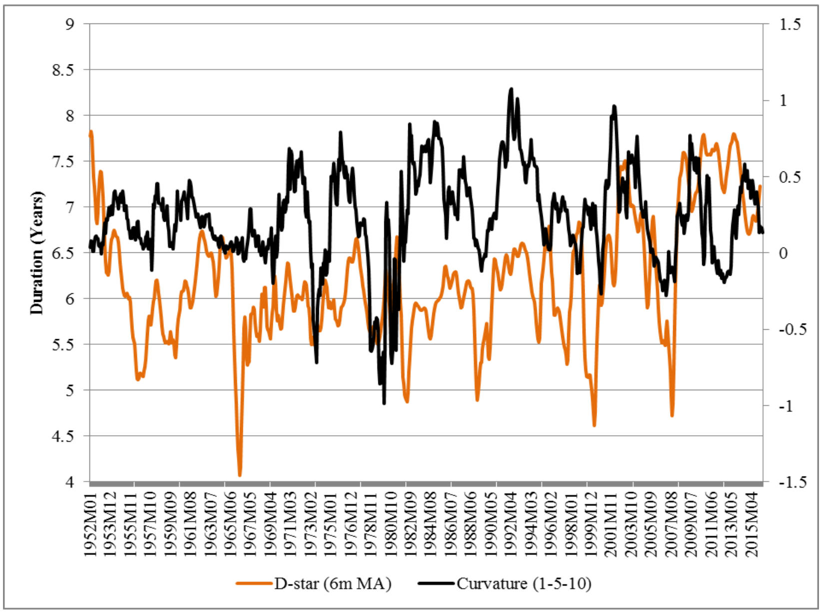
Source: Author's calculations and Federal Reserve; Comment: The chart reports the correlation between 6-month centred moving average (CMA) estimates of D-star – the position of the hump in years along the maturity axis – and the 10-year less 1-year Treasury yield curve slope. The correlation coefficient is high and positive at 0.577, but there are lengthy periods, such as the mid-1980s and early-1990s when the D-star data was less volatile. Ahead of recessionary periods, D-star moves more sharply lower.

I also take some additional cross-checks on the consistency of D-star using more familiar yield curve factors from the literature. D-star correlates negatively (-0.198) with the bond forecasting factor devised by Cochrane and Piazzesi (2006), which seems plausible. Although theoretically related to the forward rate identified by Fama (1986), neither D-star measure is strongly positively correlated with this peak forward rate (0.228 and 0.209, using daily data)[31]. *Pace* the concerns of Gilli, Grosse and Schumann (2010) about the robustness of empirical estimates of the Nelson-Siegel-Svensson yield curve parameters, D-star positively correlates, as expected, with the tau_1 'shape' parameter (0.163, 1961-2016, rising to 0.306 for the recent period since 2000) as estimated by Gurkaynak, Sack and Wright (2006). Fontaine and Garcia (2011) calculate the price of funding liquidity using 'on/ off-the-run' Treasury data, while Pastor and Stambaugh (2003) estimate equity market liquidity from regression analysis (see

[31] Using the Gurkaynak, Sack and Wright (2006) term structure data

Brunnermeier, 2008). D-star shows a modest correlation with the Fontaine-Garcia factor, with an expected negative sign (-0.154) indicating that tighter liquidity conditions reduce investment horizons and should lead to a flatter yield curve. However, D-star correlates positively with the Pastor and Stambaugh measure of equity market liquidity (0.190) and shows one-way Granger causality (p=0.037, 0.478) fourteen months ahead. This is consistent with the interpretation that a more favourable future economic outlook, signalled by a longer investment horizon and larger D-star, will encourage a switch into equities and other long duration assets, including capital equipment. In fact, D-star also positively correlates with the US ISM Purchasing Managers' Index for manufacturing, a popular measure of business activity, 15-months ahead (0.230) and shows one-way Granger causality one-year ahead (p=0.044, 0.333). Similarly, D-star negatively correlates with the Bank of America/ Merrill Lynch high yield credit spread (B-BBB) 15-months ahead (0.563) – as reported earlier in Figure 2 – and again shows one-way Granger causality one-year ahead (p=0.020, 0.981).

Figure 8: D-star (6-month CMA) and Curvature (10-5-1 year), 1946-2016 (Monthly)



Source: Author's calculations and Federal Reserve; Comment: The chart reports the correlation between 6-month centred moving average (CMA) estimates of D-star – the position of the hump in years along the maturity axis – and the 10-year, 5-year, 1-year butterfly spread on the US Treasury yield curve. The correlation coefficient is moderately positive at 0.142. Again there are lengthy periods, such as the late-1960s, mid-1980s and early-1990s when the D-star data was less volatile. Ahead of recessionary periods, D-star moves more sharply lower.

Lower investor demand for safe asset duration is also implied by the positive correlation between D-star and: (1) the annual growth rate of the US monetary base (0.317) and (2) movements in the absolute size of the Federal Reserve's balance sheet (0.389) through the period of the GFC and the subsequent LSAP (2007-15). While Federal Reserve Treasury purchases directly reduce duration risk, the greater supply of the zero duration asset, i.e. cash, reduces systemic risks and therefore allows investors to cut back on their demands for safe assets, such as 10-year Treasury bonds. The supply and demand for maturity may consequently be linked. With larger cash holdings, investors can lengthen their existing asset duration through net purchases of riskier assets, such as equities, corporate debt or ultra-long maturity Treasuries, and still match the duration of their liabilities. To the extent that Federal Reserve LSAP reduces the effective supply of longer-dated debt and boosts cash holdings, term premia should generally fall, but the effect on D-star is not certain because it depends on the pattern and not just the level of term premia. The maturity of bonds demanded and supplied matters for D-star and Section 3.3 showed that these two effects can counterbalance at different tenors. This may be another reason why the data only show a modest positive correlation between D-star and the average level of the Treasury term premia over the period 1961-2016 (0.197, rising to 0.337 since year 2000), based on the calculations of Adrian et al. (2014), after normalising for the effects of inflation[32]. The two series only rise and fall together 48% of the time and in 26% of cases D-star expands (contracts) while average term premia fall (increase).

3.8 A Comparison With Principal Components & Kalman Factors

The principal components decomposition of the term structure also provides a benchmark against which to test the efficacy of D-star in explaining the structure of yields. I compare regression results using the first three principal components, calculated from 1-year through 20-year monthly Treasury yields over the 1954-2016 period, with an alternative decomposition that takes the 1-year spot rate, the 10-year less 1-year forward spread (slope); the 1-5-10 year forward butterfly spread (curvature); D-star (position of the hump) and the maturity of the outstanding stock of US Treasuries

[32] This eliminates inflation effects from the nominal term premia to create a stationary series for the 'real' term premia

held by the private sector, as a measure of supply. Because some of these factors include 1, 5 and 10-year yields, regression comparisons are not performed for these maturities:

$$y_{m,t} = B_0^m + \beta_1^m y_{1,t} + \beta_2^m(y_{10,t} - y_{1,t}) + \beta_3^m\left(y_{5,t} - (y_{10,t} + y_{1,t})\right) + \beta_4^m D_t^* + \beta_5^m M_t + \varepsilon_t$$

where $y_{m,t}$ is the spot yield for maturity m at time t; D_t^* is D-star; M_t is the average maturity of the outstanding stock of Treasuries held by the private sector; ε_t is a random error term, and the β^m's are the parameters to be estimated.

Table 6: Regression of Selected US Treasury Yields on Various Yield Curve Factors, 1954-2016 (Monthly)

	3 x Principal Components	5-Factor Alternative Decomposition (level, slope, curvature, hump position & supply)		
Maturity	R^2 (BIC)	R^2 {BIC ex.all} (BIC) [BIC +D^*]	D-star Loading	Maturity Supply Loading
y_2	0.9996 (-2.504)	0.9991 {-1.595} (-1.729) [-1.675]	-0.076*** (0.022)	0.029*** (0.010)
y_3	0.9997 (-3.028)	0.9995 {-2.305} (-2.341) [-2.320]	-0.034** (0.016)	0.013* (0.007)
y_7	0.9998 (-3.680)	0.9997 {-3.230} (-3.244) [-3.224]	-0.007 (0.010)	0.010** (0.005)
y_{20}	0.9997 (-3.408)	0.9943 {-0.315} (-0.299) [-0.306]	0.039 (0.045)	0.010 (0.027)
y_{30}	0.9978 (-1.074)	0.9986 {-1.446} (-1.492) [-1.491]	0.068*** (0.020)	0.022 (0.016)

Source: Regression estimates; Comment: Estimated with constant term included, but not shown. Figures in brackets beneath loadings are adjusted standard errors. Single, double, triple asterisks refer, respectively, to 10%, 5% and 1% significance levels. D^* is a 6-month centred moving average of raw data. Figures in curly brackets refer to the BIC without D-star and maturity supply. Figures in square brackets refer to the BIC with D-star, but without maturity supply. BIC is the Bayesian Information Criteria. y_2 denotes the spot yield of the 2-year maturity; y_3 that of the 3-year maturity, etc.

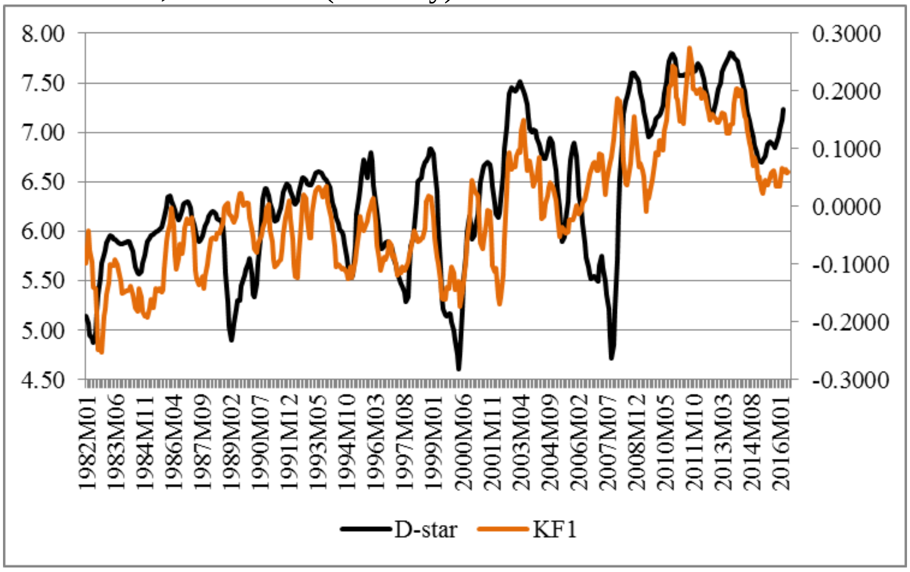
The results of a regression of Treasury spot yields on these various factors are summarised in Table 6. They generally show that the alternative decomposition performs nearly as well as the principal components, and in the case of the 'out-of-sample' 30-year bond it outperforms, based on BIC (Bayesian Information Criteria). R-squared is shown for reference alongside. The inclusion of D-star also improves the BIC statistic (i.e. lowers it) compared to 3-factor level, slope and curvature model in three cases and slightly worsens the BIC for the 7-year and 20-year bonds. The inclusion of the maturity supply factor marginally improves the BIC, suggesting 4-factors are sufficient. Apart from the 7-year and 20-year bond, the D-star factor is significant at the

5% level and for the 2 and 30-year bond it is significant at the 1% level. The signs on the estimated D-star coefficients seem plausible. They rise progressively from a negative loading on the 2-year bond to a positive loading on the 30-year bond and approximately sum to zero. This says that as D-star lengthens it raises yields on longer-dated bonds and reduces yields on shorter-dated bonds: each one year extension in D-star subtracts around 7-8bp from 2-year yields and adds the same to 30-year yields. Therefore, the yield curve steepens as D-star lengthens: a result consistent with the interpretation that a longer D-star precedes an improving economic outlook, characterised by a different *preferred habitat*.

Assuming a downward-sloping maturity supply curve (with respect to yields), this suggests that expansions in D-star cause the demand curve for longer maturities (e.g. 10-year Treasuries) to decrease (shift leftwards) and the demand curve for shorter maturities to increase (shift rightwards). This reduced demand for safe asset Treasuries and corresponding increase in their holdings of long-duration risky assets is consistent with an improvement in investors' risk appetite. The table also shows that loadings on the supply variable (M_t) are positive at every tenor, consistent with an upward-sloping demand curve (with respect to yields), although they are only significant at lower maturities. Other things being equal, a greater supply of maturity should generally raise yields because the overall quantity of duration risk has increased.

As a final consistency check, I use a different method to estimate D-star by filtering factors from a standard affine yield curve model. The model specification is parsimonious, with only four parameters in the market price of risk and 13 parameters in total, and the parameter matrix is diagonal, allowing the identification of principal components. I compare a 6-month, centred moving average of the D-star data with the fourth Kalman factor. This Kalman factor closely correlates (0.503) with D-star, while the other three Kalman factors show significant correlations with the traditional level (0.940); slope (-0.777) and curvature (0.305) measures. Full results for 1946-2016 are reported in Appendix C. Over the more recent period since *Volcker's Great Experiment* (1979-82) with high real US interest rates, the correlation between D-star and the Kalman factor tightens to 0.729 (1982-2016). See Figure 9.

Figure 9: D-star (6-month CMA) and a Fourth Kalman Factor Filtered from Affine Yield Curve, 1982-2016 (Monthly)



Source: Author's calculations; Comment: I take a 6-month centred moving average (CMA) of the generic D-star estimates and plot this against a fourth Kalman factor (KF1) filtered from the US term structure modelled from an affine yield curve model. The three other Kalman factors correlate closely to the traditional level, slope and curvature measures. The correlation between D-star and the Kalman factor is 0.777 (0.503, 1946-2016).

3.9 Conclusion

This chapter focuses on the quantities of maturity implicitly held by different investors across the Treasury yield curve. It proposes a new decomposition of the interest rate term structure that includes an additional fourth factor, D-star, which is related to these quantities. D-star complements the traditional level, slope and curvature factors. It defines the position of the hump in the yield curve along the maturity axis. When the yield curve is symmetric and with a single hump, this is the investment time horizon associated with the maximum curvature. The new parameter is time-varying and is determined by the pattern rather than the prevailing level of term premia. A yield curve hump positioned at longer maturities implies lengthier time horizons of investors and may be consistent with more risk-seeking behaviour. Greater curvature at any point could derive from a lower term premium at longer maturities associated with a greater demand for safety at those tenors. D-star is straightforward to calculate for traditional coupon bond and zero-coupon yield curves. I estimate a 6.3 year average and a range of between 3.5 years and 8.5 years (US, 1946-2016).

D-star is closely connected with recent *preferred habitat, limits to arbitrage* and *institutional finance* models that emphasise maturity, duration and quantity effects, and it makes it easier to identify their impact on the term structure. Although these various effects are excluded from traditional term structure models, they have recently become prominent because of the LSAP and debt management operations enacted since the 2007/08 Financial Crisis, notably the attempts by policy-makers to lengthen the average maturity of the Federal Reserve's Treasury holdings. D-star may tell us something about investors' future outlook from imbalances between the supply and demand for maturity. This forward-looking information spans key macro-finance variables, such as corporate credit spreads and general investors' risk appetite. An increase in D-star may not mean a greater demand for bond duration, but it is consistent with more demand for overall asset duration and with a rise in the implied risk appetite of investors. Shifts in investors' risk appetite are better captured by expansions and contractions in D-star than by movements in the average level of bond term premia, whose message can be distorted by market volatility and by changes in the intensity of arbitrage activity. These movements in D-star measure reshufflings in the demand for different bond maturities and in the maturity mix or *preferred habitat*. The D-star data can also offer another interpretation of the 2007/08 Global Financial Crisis and Great Recession because the position of the hump on the US Treasury yield curve contracted sharply inwards from 7.5 years to 4.4 years several months before. This implies that investors' narrowed their time horizons ahead of the Crisis, consistent with a lower risk appetite, a *preferred habitat* at shorter maturities and greater demand for safe asset duration. Alongside, there occurs an associated shift of assets from, say, equities and capital goods (including unfinished projects) into long maturity Treasury bonds. The reduction in capital spending adversely affects economic activity with a lag and leads to higher default risk in the corporate bond market, which is expressed through wider credit spreads. Essentially, contractions (expansions) in investment time horizons are transmitted through an asset allocation shift between risky and safe assets, resulting in an excess demand for (supply of) safety and a fall (rise) in D-star.

D-star may, therefore, be a candidate for inclusion in the array of predictive variables monitored to ensure system-wide financial stability. But what exactly determines D-star; its transmission process following shocks; the subsequent interaction with other macro-finance variables and comparisons of D-star across the major international bond markets are areas I leave for further research. However, I conjecture that if this curvature position measure can identify a *preferred habitat*, then it should, in turn, be related to the same factors that determine this point, such as the underlying duration of investors' liabilities and their risk appetite. This could open up additional research possibilities by allowing a comparison between measures of asset and liability duration, identifying possible mismatches and modelling the subsequent adjustment process.

Appendix 3A: An Interpretation of the Position of the Yield Curve Hump

The economic meaning of the position of the yield curve hump can be understood from a second decomposition of the yield curve, based on Ilmanen (1995), which explains the sources of fixed-income returns by adding the effects of curve reshaping and convexity on returns: (1) risk premia $(h_n - y_1)$, or what I earlier describe as the *preferred habitat effect*; (2) the duration impact of expected interest rates [ibidem *duration effect*] and (3) *convexity bias*, so-called, or the option value of implied volatility [ibidem *uncertainty effect*]. Chapter 2 Appendix derives this decomposition for the steepness of the one year forward curve $(f_{n-1,n} - y_1)$ as an example. Time period subscripts have been dropped for convenience:

$$f_{n-1,n} - y_1 \approx$$

$$\underbrace{E(h_n - y_1)}_{\textit{bond risk premium}} - \left(1 + f_{n-1,n}\right) \cdot [\underbrace{-D_{n-1} \cdot E(\Delta y_{n-1})}_{\substack{\textit{duration impact}\\ \textit{of the interest rate view}}} + \underbrace{0.5Cvx_{n-1} \cdot (V(y_{n-1}))^2}_{\textit{convexity bias}}]$$

where:

$$f_{n-1,n} \approx n \cdot y_n - (n-1) \cdot y_{n-1}$$

and:

$$Cvx_n = D_n^2 - \frac{dD_n}{dy_n}$$

and let y_1 denote one period spot rates; y_t is the spot rate in period t; h_n is the one period holding period return of an n-year bond; $f_{n-1,n}$ the one period forward rate between $n-1$ and n; D_n represents *modified duration* for an n-period bond; Cvx_n is convexity and V denotes volatility (or standard deviation), where $E(\Delta y_n)^2 \approx V(\Delta y_n)^2$.

These three components contribute in different ways to each of the traditional level, slope and curvature term structure factors. For example, a large curvature around the mid-duration years can arise because of the pattern of risk premia. Sizeable risk premia, in turn, may be justified by a preferred habitat argument when there is an excess supply of maturity in this area of the curve. (From equation (3), above.) Equally, the yield curve hump may be explained by the duration impact of expected interest rate changes, since a fall in yields will deliver greater capital gains for longer duration bonds and, in order to equalise holding period returns, investors in shorter duration bonds will need to be compensated by a yield premium pick-up[33]. Consider four bonds with durations of 2,

[33] The capital gain on a bond of maturity m-years is approximately equal to $\%\Delta p_m = -D_m . \Delta y_m$, where D_m is modified duration, p_m is the price of the bond and y_m its yield. The impact of yield shocks increases with duration.

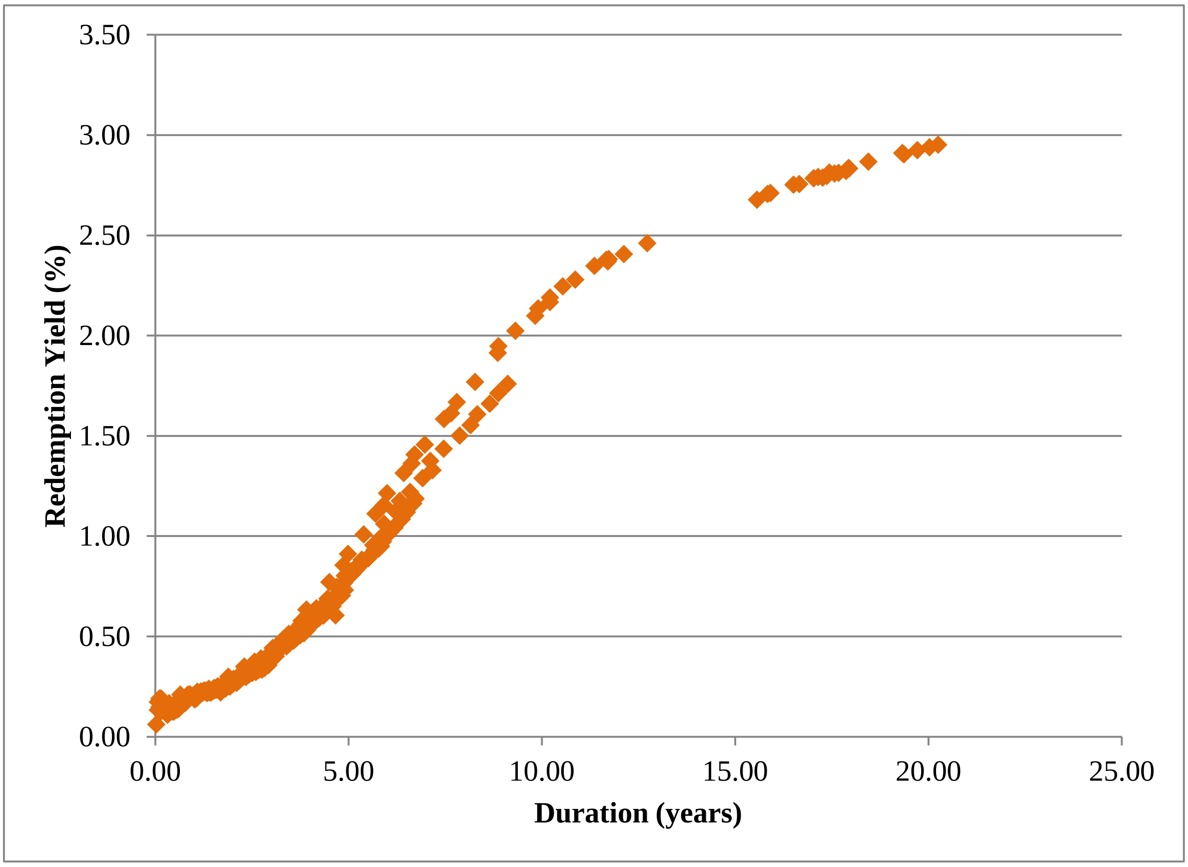
5, 7 and 10 years. Assume that 2 and 5 year interest rates remain unchanged and that rates at 7 and 10 years fall by 50bp, generating capital gains of 3.5% and 5%, respectively. For holding period returns to be equalised, the 2-year and 5-year bonds will each require an additional yield premium of 5%, and the 7-year bond an additional premium of 1.5%. This makes the yield curve more humped up to the 5-year duration. A third reason is *convexity bias*, which adjusts for expected volatility. The standard yield curve's mid-duration hump can be explained by the option value of implied volatility, which is significantly greater for longer-dated bonds since it acts through the square of duration (Cnx_n). For example, the implied value of a given volatility is four times greater at 10-years duration than at 5-years, which suggests that the 10-year bond should sell at a higher price (lower yield). Therefore, a larger-than-normal sized hump may result because investors expect relatively more volatility from longer dated bond yields. This, in turn, could describe a more uncertain future interest rate outlook.

In summary, a hump at any point on the maturity axis suggests a more uncertain and increasingly less favourable forward-looking economic outlook for all future maturities beyond that time horizon. In other words, D-star describes a boundary where there is an excess demand for duration at longer horizons, involving some combination of (1) greater rate uncertainty; (2) the likelihood of falling future yields and/ or (3) a desire for longer-dated safe Treasury bonds (Caballero, 2006), as preferred habitat investors become less risk-seeking. Consequently, this curvature peak is likely to incorporate larger term premia and expectations of subsequent falls in forward rates. Beyond this horizon, the greater demands for safety result in lower term premia. It may also follow that, when Treasury supply comprises relatively longer maturities, financial systems are less vulnerable to risk than if positions have to be more frequently refinanced and so potentially clashing with private sector funding needs. The reverse arguments should explain a more linear yield curve, which by implication points towards a more certain and favourable future economic outlook characterised by rising short-term interest rates and low volatility. Therefore, if the position of the hump delineates these regimes, a hump which occurs at a near-term maturity describes a less attractive approaching business outlook than a hump that occurs at a longer maturity. It follows that the investment time horizon should lengthen (contract) *pari passu* with increases (decreases) in the position of the curvature peak. More distant values of this peak may be associated with a larger risk appetite among investors.

Appendix 3B: US Treasury Term Structure 30/12/2012

D-star and D-peak are calculated for all 265 outstanding US Treasury issues on 30/12/2012 using equation (4) as described in section 3.4. These securities are a mixture of on-the-run and off-the-run coupon bonds with an average duration of 4.87 years and an average yield of 82bp. Figure B1 plots the data and the following table reports the corresponding redemption yields and Macaulay durations, and the contributions of each to D-star. The Treasury term structure in the chart is upward sloping with a mid-duration hump. The curvature peak occurs at a duration of 10.55 years and D-star is positioned at 8.26 years.

Figure B1: US Treasury Term Structure, 30th December, 2012



From section 3.4, the distance measure (d_{m0}) for each time-horizon (m_0) is defined as:

$$d_{m0} = \frac{|y_{m0} - a - bm_0|}{\sqrt{(b^2 + 1)}}$$

where $y=a+b.m$ is a line joining the extremes of the yield curve, and, D-star (D_t^*), the distance-weighted average of these time horizons is calculated from:

$$D_t^* \cong \frac{\sum_{m=1}^{n} m \cdot d_{m,t}}{\sum_{m=1}^{n} d_{m,t}}$$

Treasury Issues Outstanding 30/12/2012	Duration (m, years)	Yield (%)	d_m	$m*d_m$
US TREASURY 1985 10 5/8% 15/08/15 2015 - RED. YIELD	2.311	0.349	0.036	0.083
US TREASURY 1985 11 1/4% 15/02/15 2015 - RED. YIELD	1.900	0.299	0.028	0.053
US TREASURY 1985 9 7/8% 15/11/15 2015 - RED. YIELD	2.579	0.373	0.050	0.130
US TREASURY 1986 7 1/2% 15/11/16 2016 - RED. YIELD	3.463	0.513	0.037	0.128
US TREASURY 1986 7 1/4% 15/05/16 2016 - RED. YIELD	3.054	0.442	0.049	0.151
US TREASURY 1986 9 1/4% 15/02/16 2016 - RED. YIELD	2.749	0.389	0.058	0.160
US TREASURY 1987 8 3/4% 15/05/17 2017 - RED. YIELD	3.795	0.577	0.020	0.076
US TREASURY 1987 8 7/8% 15/08/17 2017 - RED. YIELD	3.917	0.633	0.017	0.068
US TREASURY 1988 9 1/8% 15/05/18 2018 - RED. YIELD	4.515	0.770	0.069	0.312
US TREASURY 1988 9% 15/11/18 2018 - RED. YIELD	4.883	0.855	0.101	0.494
US TREASURY 1989 8 1/8% 15/08/19 2019 - RED. YIELD	5.401	1.008	0.180	0.970
US TREASURY 1989 8 7/8% 15/02/19 2019 - RED. YIELD	4.995	0.910	0.140	0.698
US TREASURY 1990 8 1/2% 15/02/20 2020 - RED. YIELD	5.708	1.112	0.239	1.362
US TREASURY 1990 8 3/4% 15/05/20 2020 - RED. YIELD	5.924	1.154	0.250	1.481
US TREASURY 1990 8 3/4% 15/08/20 2020 - RED. YIELD	6.006	1.214	0.297	1.785
US TREASURY 1991 7 7/8% 15/02/21 2021 - RED. YIELD	6.436	1.313	0.335	2.155
US TREASURY 1991 8 1/8% 15/05/21 2021 - RED. YIELD	6.646	1.362	0.354	2.351
US TREASURY 1991 8 1/8% 15/08/21 2021 - RED. YIELD	6.720	1.406	0.387	2.599
US TREASURY 1991 8% 15/11/21 2021 - RED. YIELD	6.985	1.456	0.399	2.786
US TREASURY 1992 7 1/4% 15/08/22 2022 - RED. YIELD	7.477	1.583	0.455	3.399
US TREASURY 1992 7 5/8% 15/11/22 2022 - RED. YIELD	7.665	1.613	0.457	3.506
US TREASURY 1993 6 1/4% 15/08/23 2023 - RED. YIELD	8.284	1.768	0.523	4.335
US TREASURY 1993 7 1/8% 15/02/23 2023 - RED. YIELD	7.812	1.669	0.492	3.843
US TREASURY 1994 7 1/2% 15/11/24 2024 - RED. YIELD	8.873	1.914	0.585	5.186
US TREASURY 1995 6 7/8% 15/08/25 2025 - RED. YIELD	9.327	2.023	0.628	5.860
US TREASURY 1995 7 5/8% 15/02/25 2025 - RED. YIELD	8.887	1.947	0.616	5.470
US TREASURY 1996 6 1/2% 15/11/26 S - RED. YIELD	10.223	2.168	0.645	6.594
US TREASURY 1996 6 3/4% 15/08/26 2026 - RED. YIELD	9.911	2.136	0.657	6.515
US TREASURY 1996 6% 15/02/26 2026 - RED. YIELD	9.838	2.099	0.631	6.210
US TREASURY 1997 6 1/8% 15/11/27 20-2027 - RED. YIELD	10.873	2.279	0.663	7.211
US TREASURY 1997 6 3/8% 15/08/27 S - RED. YIELD	10.553	2.245	0.675	7.118
US TREASURY 1997 6 5/8% 15/02/27 S - RED. YIELD	10.219	2.190	0.667	6.819
US TREASURY 1998 5 1/2% 15/08/28 BONDS O - RED. YIELD	11.375	2.347	0.660	7.505
US TREASURY 1998 5 1/4% 15/11/28 BONDS O - RED. YIELD	11.717	2.370	0.634	7.430
US TREASURY 1999 5 1/4% 15/02/29 2029 - RED. YIELD	11.745	2.381	0.641	7.526
US TREASURY 1999 6 1/8% 15/08/29 AUGUST - RED. YIELD	11.680	2.377	0.646	7.548
US TREASURY 2000 6 1/4% 15/05/30 MAY 203 - RED. YIELD	12.135	2.407	0.611	7.415
US TREASURY 2001 5 3/8% 15/02/31 FEBRUAR - RED. YIELD	12.739	2.460	0.578	7.369
US TREASURY 2003 3 5/8% 15/05/13 B-2013 - RED. YIELD	0.367	0.166	0.057	0.021
US TREASURY 2003 3 7/8% 15/02/13 A-2013 - RED. YIELD	0.123	0.190	0.116	0.014
US TREASURY 2003 4 1/4% 15/08/13 D-2013 - RED. YIELD	0.608	0.181	0.038	0.023
US TREASURY 2003 4 1/4% 15/11/13 E-2013 - RED. YIELD	0.860	0.210	0.031	0.027

US TREASURY 2004 4 1/4% 15/08/14 E-2014 - RED. YIELD	1.558	0.240	0.038	0.059
US TREASURY 2004 4 1/4% 15/11/14 F-2014 - RED. YIELD	1.810	0.269	0.044	0.080
US TREASURY 2004 4 3/4% 15/05/14 C-2014 - RED. YIELD	1.332	0.230	0.015	0.020
US TREASURY 2004 4% 15/02/14 B-2014 - RED. YIELD	1.094	0.224	0.012	0.013
US TREASURY 2005 4 1/2% 15/11/15 F-2015 - RED. YIELD	2.717	0.350	0.093	0.252
US TREASURY 2005 4 1/4% 15/08/15 E-2015 - RED. YIELD	2.473	0.347	0.061	0.151
US TREASURY 2005 4 1/8% 15/05/15 C-2015 - RED. YIELD	2.270	0.323	0.056	0.127
US TREASURY 2005 4% 15/02/15 B-2015 - RED. YIELD	2.029	0.287	0.058	0.117
US TREASURY 2006 4 1/2% 15/02/16 B-2016 - RED. YIELD	2.912	0.403	0.068	0.199
US TREASURY 2006 4 1/2% 15/02/36 FEBRUAR - RED. YIELD	15.579	2.677	0.392	6.106
US TREASURY 2006 4 5/8% 15/11/16 F-2016 - RED. YIELD	3.595	0.524	0.045	0.160
US TREASURY 2006 4 7/8% 15/08/16 E-2016 - RED. YIELD	3.323	0.486	0.043	0.144
US TREASURY 2006 5 1/8% 15/05/16 C-2016 - RED. YIELD	3.130	0.447	0.055	0.171
US TREASURY 2007 4 1/2% 15/05/17 C-2017 - RED. YIELD	4.025	0.606	0.024	0.098
US TREASURY 2007 4 1/4% 15/11/17 F-2017 - RED. YIELD	4.469	0.688	0.006	0.027
US TREASURY 2007 4 3/4% 15/02/37 FEBRUAR - RED. YIELD	15.848	2.706	0.382	6.058
US TREASURY 2007 4 3/4% 15/08/17 E-2017 - RED. YIELD	4.180	0.640	0.012	0.051
US TREASURY 2007 4 5/8% 15/02/17 B-2017 - RED. YIELD	3.774	0.560	0.034	0.128
US TREASURY 2007 5% 15/05/37 BONDS O - RED. YIELD	15.929	2.710	0.375	5.975
US TREASURY 2008 1 1/2% 31/12/13 T-2013 - RED. YIELD	0.993	0.204	0.007	0.007
US TREASURY 2008 2 1/2% 31/03/13 H-2013 - RED. YIELD	0.244	0.140	0.050	0.012
US TREASURY 2008 2 3/4% 28/02/13 G-2013 - RED. YIELD	0.159	0.190	0.111	0.018
US TREASURY 2008 2 3/4% 31/10/13 R-2013 - RED. YIELD	0.823	0.203	0.030	0.024
US TREASURY 2008 2 7/8% 31/01/13 F-2013 - RED. YIELD	0.082	0.173	0.105	0.009
US TREASURY 2008 2% 30/11/13 S-2013 - RED. YIELD	0.907	0.210	0.025	0.023
US TREASURY 2008 3 1/2% 15/02/18 B-2018 - RED. YIELD	4.710	0.747	0.018	0.084
US TREASURY 2008 3 1/2% 31/05/13 L-2013 - RED. YIELD	0.411	0.144	0.030	0.012
US TREASURY 2008 3 1/8% 30/04/13 K-2013 - RED. YIELD	0.326	0.143	0.041	0.013
US TREASURY 2008 3 1/8% 30/09/13 Q-2013 - RED. YIELD	0.737	0.180	0.019	0.014
US TREASURY 2008 3 1/8% 31/08/13 P-2013 - RED. YIELD	0.655	0.209	0.059	0.039
US TREASURY 2008 3 3/4% 15/11/18 F-2018 - RED. YIELD	5.351	0.882	0.061	0.329
US TREASURY 2008 3 3/8% 30/06/13 M-2013 - RED. YIELD	0.493	0.156	0.030	0.015
US TREASURY 2008 3 3/8% 31/07/13 N-2013 - RED. YIELD	0.570	0.157	0.021	0.012
US TREASURY 2008 3 7/8% 15/05/18 C-2018 - RED. YIELD	4.917	0.802	0.044	0.216
US TREASURY 2008 4 1/2% 15/05/38 BONDS O - RED. YIELD	16.672	2.755	0.314	5.238
US TREASURY 2008 4 3/8% 15/02/38 BONDS O - RED. YIELD	16.524	2.751	0.332	5.479
US TREASURY 2008 4% 15/08/18 E-2018 - RED. YIELD	5.072	0.823	0.043	0.216
US TREASURY 2009 1 3/4% 31/01/14 G-2014 - RED. YIELD	1.068	0.212	0.004	0.005
US TREASURY 2009 1 3/4% 31/03/14 J-2014 - RED. YIELD	1.230	0.222	0.009	0.011
US TREASURY 2009 1 7/8% 28/02/14 H-2014 - RED. YIELD	1.144	0.217	0.002	0.002
US TREASURY 2009 1 7/8% 30/04/14 L-2014 - RED. YIELD	1.311	0.224	0.019	0.025
US TREASURY 2009 2 1/4% 31/05/14 M-2014 - RED. YIELD	1.393	0.238	0.016	0.023
US TREASURY 2009 2 1/8% 30/11/14 T-2014 - RED. YIELD	1.879	0.262	0.061	0.114
US TREASURY 2009 2 3/4% 15/02/19 B-2019 - RED. YIELD	5.652	0.955	0.091	0.513

US TREASURY 2009 2 3/4% 30/11/16 R-2016 - RED. YIELD	3.737	0.521	0.068	0.253
US TREASURY 2009 2 3/8% 30/09/14 R-2014 - RED. YIELD	1.709	0.237	0.062	0.106
US TREASURY 2009 2 3/8% 31/03/16 H-2016 - RED. YIELD	3.121	0.422	0.079	0.245
US TREASURY 2009 2 3/8% 31/08/14 Q-2014 - RED. YIELD	1.627	0.250	0.037	0.060
US TREASURY 2009 2 3/8% 31/10/14 S-2014 - RED. YIELD	1.794	0.264	0.047	0.085
US TREASURY 2009 2 5/8% 29/02/16 G-2016 - RED. YIELD	3.028	0.396	0.091	0.276
US TREASURY 2009 2 5/8% 30/04/16 J-2016 - RED. YIELD	3.192	0.432	0.078	0.250
US TREASURY 2009 2 5/8% 30/06/14 N-2014 - RED. YIELD	1.473	0.229	0.036	0.053
US TREASURY 2009 2 5/8% 31/07/14 P-2014 - RED. YIELD	1.539	0.242	0.033	0.051
US TREASURY 2009 2 5/8% 31/12/14 U-2014 - RED. YIELD	1.957	0.254	0.080	0.156
US TREASURY 2009 3 1/2% 15/02/39 BONDS O - RED. YIELD	17.690	2.811	0.225	3.986
US TREASURY 2009 3 1/4% 30/06/16 L-2016 - RED. YIELD	3.331	0.457	0.073	0.244
US TREASURY 2009 3 1/4% 31/05/16 K-2016 - RED. YIELD	3.249	0.447	0.072	0.235
US TREASURY 2009 3 1/4% 31/07/16 M-2016 - RED. YIELD	3.367	0.468	0.068	0.228
US TREASURY 2009 3 1/4% 31/12/16 S-2016 - RED. YIELD	3.793	0.536	0.061	0.232
US TREASURY 2009 3 1/8% 15/05/19 C-2019 - RED. YIELD	5.842	0.992	0.100	0.587
US TREASURY 2009 3 1/8% 31/10/16 Q-2016 - RED. YIELD	3.633	0.516	0.058	0.211
US TREASURY 2009 3 3/8% 15/11/19 F-2019 - RED. YIELD	6.223	1.123	0.176	1.097
US TREASURY 2009 3 5/8% 15/08/19 E-2019 - RED. YIELD	5.934	1.061	0.156	0.925
US TREASURY 2009 3% 30/09/16 P-2016 - RED. YIELD	3.547	0.495	0.066	0.235
US TREASURY 2009 3% 31/08/16 N-2016 - RED. YIELD	3.464	0.495	0.055	0.190
US TREASURY 2009 4 1/2% 15/08/39 BONDS O - RED. YIELD	17.045	2.784	0.290	4.947
US TREASURY 2009 4 1/4% 15/05/39 BONDS O - RED. YIELD	17.274	2.786	0.260	4.494
US TREASURY 2009 4 3/8% 15/11/39 BONDS O - RED. YIELD	17.384	2.796	0.254	4.414
US TREASURY 2010 1 1/4% 30/09/15 R-2015 - RED. YIELD	2.695	0.338	0.102	0.274
US TREASURY 2010 1 1/4% 31/08/15 S - RED. YIELD	2.613	0.334	0.094	0.245
US TREASURY 2010 1 1/4% 31/10/15 S-2015 - RED. YIELD	2.780	0.344	0.108	0.300
US TREASURY 2010 1 1/8% 15/06/13 S - RED. YIELD	0.452	0.125	0.005	0.002
US TREASURY 2010 1 3/4% 15/04/13 X-2013 - RED. YIELD	0.285	0.139	0.043	0.012
US TREASURY 2010 1 3/4% 31/07/15 P-2015 - RED. YIELD	2.511	0.329	0.084	0.211
US TREASURY 2010 1 3/8% 15/01/13 S - RED. YIELD	0.038	0.061	0.000	0.000
US TREASURY 2010 1 3/8% 15/02/13 V-2013 - RED. YIELD	0.123	0.146	0.073	0.009
US TREASURY 2010 1 3/8% 15/03/13 S - RED. YIELD	0.200	0.136	0.051	0.010
US TREASURY 2010 1 3/8% 15/05/13 Y-2013 - RED. YIELD	0.367	0.133	0.025	0.009
US TREASURY 2010 1 3/8% 30/11/15 S - RED. YIELD	2.857	0.362	0.100	0.286
US TREASURY 2010 1 7/8% 30/06/15 N-2015 - RED. YIELD	2.444	0.318	0.085	0.209
US TREASURY 2010 1 7/8% 30/09/17 Q-2017 - RED. YIELD	4.549	0.682	0.023	0.106
US TREASURY 2010 1 7/8% 31/08/17 S - RED. YIELD	4.466	0.661	0.032	0.144
US TREASURY 2010 1 7/8% 31/10/17 R-2017 - RED. YIELD	4.633	0.696	0.021	0.099
US TREASURY 2010 1% 15/07/13 AA-2013 - RED. YIELD	0.531	0.145	0.014	0.007
US TREASURY 2010 1/2% 15/10/13 AD-2013 - RED. YIELD	0.784	0.168	0.001	0.001
US TREASURY 2010 1/2% 15/11/13 AE-2013 - RED. YIELD	0.869	0.189	0.009	0.008
US TREASURY 2010 2 1/2% 30/04/15 L-2015 - RED. YIELD	2.264	0.309	0.069	0.156
US TREASURY 2010 2 1/2% 30/06/17 M-2017 - RED. YIELD	4.288	0.628	0.039	0.169

US TREASURY 2010 2 1/2% 31/03/15 J-2015 - RED. YIELD	2.182	0.279	0.087	0.191
US TREASURY 2010 2 1/4% 30/11/17 S - RED. YIELD	4.680	0.694	0.030	0.139
US TREASURY 2010 2 1/4% 31/01/15 G-2015 - RED. YIELD	2.026	0.278	0.066	0.135
US TREASURY 2010 2 1/8% 31/05/15 M-2015 - RED. YIELD	2.356	0.319	0.072	0.170
US TREASURY 2010 2 1/8% 31/12/15 S - RED. YIELD	2.916	0.369	0.102	0.298
US TREASURY 2010 2 3/4% 31/05/17 L-2017 - RED. YIELD	4.187	0.612	0.041	0.173
US TREASURY 2010 2 3/4% 31/12/17 S - RED. YIELD	4.719	0.706	0.024	0.112
US TREASURY 2010 2 3/8% 28/02/15 H-2015 - RED. YIELD	2.100	0.284	0.071	0.148
US TREASURY 2010 2 3/8% 31/07/17 S - RED. YIELD	4.335	0.649	0.025	0.110
US TREASURY 2010 2 5/8% 15/08/20 E-2020 - RED. YIELD	6.930	1.288	0.240	1.664
US TREASURY 2010 2 5/8% 15/11/20 F-2020 - RED. YIELD	7.180	1.328	0.244	1.753
US TREASURY 2010 3 1/2% 15/05/20 C-2020 - RED. YIELD	6.602	1.220	0.219	1.444
US TREASURY 2010 3 1/4% 31/03/17 J-2017 - RED. YIELD	3.985	0.578	0.046	0.183
US TREASURY 2010 3 1/8% 30/04/17 K-2017 - RED. YIELD	4.076	0.601	0.036	0.148
US TREASURY 2010 3 1/8% 31/01/17 G-2017 - RED. YIELD	3.832	0.550	0.053	0.203
US TREASURY 2010 3 5/8% 15/02/20 B-2020 - RED. YIELD	6.339	1.175	0.212	1.342
US TREASURY 2010 3 7/8% 15/08/40 BONDS O - RED. YIELD	17.949	2.835	0.213	3.822
US TREASURY 2010 3% 28/02/17 G-2017 - RED. YIELD	3.918	0.578	0.036	0.143
US TREASURY 2010 3/4% 15/08/13 AB-2013 - RED. YIELD	0.617	0.139	0.004	0.002
US TREASURY 2010 3/4% 15/09/13 AC-2013 - RED. YIELD	0.702	0.164	0.009	0.006
US TREASURY 2010 3/4% 15/12/13 S - RED. YIELD	0.951	0.204	0.012	0.012
US TREASURY 2010 4 1/4% 15/11/40 BONDS O - RED. YIELD	17.880	2.821	0.208	3.724
US TREASURY 2010 4 3/8% 15/05/40 BONDS O - RED. YIELD	17.578	2.808	0.238	4.190
US TREASURY 2010 4 5/8% 15/02/40 BONDS O - RED. YIELD	17.157	2.791	0.281	4.817
US TREASURY 2011 1 1/2% 30/06/16 Z-2016 - RED. YIELD	3.410	0.450	0.091	0.311
US TREASURY 2011 1 1/2% 31/07/16 AA-2016 - RED. YIELD	3.470	0.463	0.087	0.302
US TREASURY 2011 1 1/2% 31/08/18 P-2018 - RED. YIELD	5.428	0.876	0.045	0.242
US TREASURY 2011 1 1/4% 15/02/14 S - RED. YIELD	1.113	0.214	0.000	0.000
US TREASURY 2011 1 1/4% 15/03/14 X-2014 - RED. YIELD	1.189	0.225	0.001	0.001
US TREASURY 2011 1 1/4% 15/04/14 Y-2014 - RED. YIELD	1.274	0.229	0.008	0.010
US TREASURY 2011 1 3/4% 31/05/16 Y-2016 - RED. YIELD	3.316	0.448	0.081	0.268
US TREASURY 2011 1 3/4% 31/10/18 R-2018 - RED. YIELD	5.560	0.903	0.052	0.291
US TREASURY 2011 1 3/8% 30/09/18 Q-2018 - RED. YIELD	5.529	0.890	0.044	0.243
US TREASURY 2011 1 3/8% 30/11/18 S-2018 - RED. YIELD	5.696	0.932	0.062	0.356
US TREASURY 2011 1% 15/01/14 S - RED. YIELD	1.030	0.186	0.017	0.017
US TREASURY 2011 1% 15/05/14 S - RED. YIELD	1.358	0.218	0.031	0.042
US TREASURY 2011 1% 30/09/16 AC-2016 - RED. YIELD	3.668	0.493	0.086	0.316
US TREASURY 2011 1% 31/08/16 AB-2016 - RED. YIELD	3.586	0.479	0.088	0.315
US TREASURY 2011 1% 31/10/16 AD-2016 - RED. YIELD	3.762	0.506	0.086	0.323
US TREASURY 2011 1/2% 15/08/14 AC-2014 - RED. YIELD	1.610	0.235	0.050	0.081
US TREASURY 2011 1/2% 15/10/14 AE-2014 - RED. YIELD	1.777	0.247	0.061	0.109
US TREASURY 2011 1/4% 15/09/14 AD-2014 - RED. YIELD	1.699	0.220	0.077	0.131
US TREASURY 2011 1/4% 15/12/14 AG-2014 - RED. YIELD	1.947	0.250	0.083	0.161
US TREASURY 2011 1/4% 30/11/13 AS-2013 - RED. YIELD	0.911	0.195	0.009	0.009

US TREASURY 2011 1/4% 31/10/13 AR-2013 - RED. YIELD	0.829	0.177	0.004	0.003
US TREASURY 2011 1/8% 30/09/13 AQ-2013 - RED. YIELD	0.744	0.165	0.003	0.002
US TREASURY 2011 1/8% 31/08/13 AP-2013 - RED. YIELD	0.662	0.170	0.020	0.013
US TREASURY 2011 2 1/4% 31/03/16 V-2016 - RED. YIELD	3.127	0.400	0.101	0.316
US TREASURY 2011 2 1/4% 31/07/18 N-2018 - RED. YIELD	5.241	0.853	0.048	0.254
US TREASURY 2011 2 1/8% 15/08/21 E-2021 - RED. YIELD	7.882	1.500	0.315	2.485
US TREASURY 2011 2 1/8% 29/02/16 U-2016 - RED. YIELD	3.051	0.390	0.101	0.307
US TREASURY 2011 2 3/4% 28/02/18 H-2018 - RED. YIELD	4.823	0.749	0.005	0.022
US TREASURY 2011 2 3/8% 30/06/18 M-2018 - RED. YIELD	5.197	0.830	0.032	0.164
US TREASURY 2011 2 3/8% 31/05/18 L-2018 - RED. YIELD	5.114	0.811	0.025	0.126
US TREASURY 2011 2 5/8% 30/04/18 K-2018 - RED. YIELD	5.003	0.797	0.026	0.133
US TREASURY 2011 2 5/8% 31/01/18 S - RED. YIELD	4.759	0.739	0.003	0.015
US TREASURY 2011 2 7/8% 31/03/18 J-2018 - RED. YIELD	4.894	0.767	0.012	0.059
US TREASURY 2011 2% 15/11/21 F-2021 - RED. YIELD	8.169	1.554	0.328	2.679
US TREASURY 2011 2% 30/04/16 X-2016 - RED. YIELD	3.220	0.434	0.081	0.259
US TREASURY 2011 2% 31/01/16 S - RED. YIELD	2.978	0.382	0.097	0.290
US TREASURY 2011 3 1/8% 15/05/21 C-2021 - RED. YIELD	7.470	1.436	0.310	2.316
US TREASURY 2011 3 1/8% 15/11/41 BONDS O - RED. YIELD	19.375	2.904	0.079	1.540
US TREASURY 2011 3 3/4% 15/08/41 BONDS O - RED. YIELD	18.454	2.867	0.173	3.197
US TREASURY 2011 3 5/8% 15/02/21 S - RED. YIELD	7.121	1.374	0.298	2.124
US TREASURY 2011 3/4% 15/06/14 AA-2014 - RED. YIELD	1.445	0.219	0.042	0.061
US TREASURY 2011 3/4% 31/03/13 AJ-2013 - RED. YIELD	0.244	0.141	0.050	0.012
US TREASURY 2011 3/8% 15/11/14 AF-2014 - RED. YIELD	1.863	0.251	0.069	0.129
US TREASURY 2011 3/8% 30/06/13 AM-2013 - RED. YIELD	0.493	0.125	0.001	0.001
US TREASURY 2011 3/8% 31/07/13 AN-2013 - RED. YIELD	0.577	0.135	0.003	0.002
US TREASURY 2011 4 3/4% 15/02/41 S - RED. YIELD	17.448	2.813	0.262	4.568
US TREASURY 2011 4 3/8% 15/05/41 BONDS O - RED. YIELD	17.964	2.834	0.209	3.760
US TREASURY 2011 5/8% 15/07/14 AB-2014 - RED. YIELD	1.523	0.228	0.045	0.068
US TREASURY 2011 5/8% 28/02/13 AH-2013 - RED. YIELD	0.159	0.127	0.048	0.008
US TREASURY 2011 5/8% 30/04/13 AK-2013 - RED. YIELD	0.326	0.109	0.007	0.002
US TREASURY 2011 5/8% 31/01/13 AG-2013 - RED. YIELD	0.082	0.133	0.066	0.005
US TREASURY 2011 7/8% 30/11/16 AE-2016 - RED. YIELD	3.852	0.516	0.089	0.344
US TREASURY 2012 1 1/2% 31/03/19 J-2019 - RED. YIELD	5.967	0.995	0.087	0.516
US TREASURY 2012 1 1/4% 30/04/19 K-2019 - RED. YIELD	6.091	1.020	0.093	0.567
US TREASURY 2012 1 1/4% 31/01/19 G-2019 - RED. YIELD	5.848	0.950	0.058	0.339
US TREASURY 2012 1 1/4% 31/10/19 R-2019 - RED. YIELD	6.554	1.139	0.145	0.953
US TREASURY 2012 1 1/8% 31/05/19 L-2019 - RED. YIELD	6.198	1.041	0.099	0.616
US TREASURY 2012 1 1/8% 31/12/19 T-2019 - RED. YIELD	6.746	1.186	0.165	1.116
US TREASURY 2012 1 3/4% 15/05/22 C-2022 - RED. YIELD	8.664	1.660	0.363	3.146
US TREASURY 2012 1 3/8% 28/02/19 H-2019 - RED. YIELD	5.903	0.973	0.073	0.432
US TREASURY 2012 1 3/8% 31/12/18 T-2018 - RED. YIELD	5.780	0.937	0.055	0.317
US TREASURY 2012 1 5/8% 15/08/22 E-2022 - RED. YIELD	8.890	1.712	0.382	3.399
US TREASURY 2012 1 5/8% 15/11/22 F-2022 - RED. YIELD	9.132	1.760	0.395	3.610
US TREASURY 2012 1% 30/06/19 M-2019 - RED. YIELD	6.302	1.068	0.111	0.698

US TREASURY 2012 1% 30/09/19 Q-2019 - RED. YIELD	6.521	1.119	0.130	0.851
US TREASURY 2012 1% 30/11/19 S-2019 - RED. YIELD	6.688	1.163	0.151	1.008
US TREASURY 2012 1% 31/03/17 W-2017 - RED. YIELD	4.156	0.578	0.071	0.295
US TREASURY 2012 1% 31/08/19 P-2019 - RED. YIELD	6.444	1.106	0.128	0.827
US TREASURY 2012 1/2% 31/07/17 AB-2017 - RED. YIELD	4.526	0.646	0.055	0.250
US TREASURY 2012 1/4% 15/01/15 V-2015 - RED. YIELD	2.029	0.265	0.080	0.162
US TREASURY 2012 1/4% 15/02/15 W-2015 - RED. YIELD	2.114	0.269	0.088	0.186
US TREASURY 2012 1/4% 15/05/15 Z-2015 - RED. YIELD	2.357	0.297	0.094	0.222
US TREASURY 2012 1/4% 15/07/15 AB-2015 - RED. YIELD	2.525	0.317	0.098	0.247
US TREASURY 2012 1/4% 15/08/15 AC-2015 - RED. YIELD	2.610	0.323	0.105	0.273
US TREASURY 2012 1/4% 15/09/15 AD-2015 - RED. YIELD	2.686	0.332	0.106	0.285
US TREASURY 2012 1/4% 15/10/15 S - RED. YIELD	2.771	0.333	0.117	0.324
US TREASURY 2012 1/4% 15/12/15 AG-2015 - RED. YIELD	2.938	0.356	0.118	0.347
US TREASURY 2012 1/4% 28/02/14 AJ-2014 - RED. YIELD	1.156	0.207	0.013	0.016
US TREASURY 2012 1/4% 30/04/14 AL-2014 - RED. YIELD	1.323	0.220	0.024	0.032
US TREASURY 2012 1/4% 30/06/14 AN-2014 - RED. YIELD	1.490	0.230	0.037	0.056
US TREASURY 2012 1/4% 30/09/14 AR-2014 - RED. YIELD	1.738	0.239	0.064	0.112
US TREASURY 2012 1/4% 30/11/14 AT-2014 - RED. YIELD	1.905	0.250	0.077	0.146
US TREASURY 2012 1/4% 31/01/14 AH-2014 - RED. YIELD	1.079	0.192	0.017	0.019
US TREASURY 2012 1/4% 31/03/14 AK-2014 - RED. YIELD	1.241	0.218	0.014	0.018
US TREASURY 2012 1/4% 31/05/14 AM-2014 - RED. YIELD	1.408	0.222	0.034	0.048
US TREASURY 2012 1/4% 31/08/14 AQ-2014 - RED. YIELD	1.661	0.238	0.054	0.090
US TREASURY 2012 1/4% 31/10/14 AS-2014 - RED. YIELD	1.823	0.239	0.076	0.139
US TREASURY 2012 1/8% 31/07/14 AP-2014 - RED. YIELD	1.579	0.233	0.048	0.076
US TREASURY 2012 1/8% 31/12/13 AT-2013 - RED. YIELD	0.996	0.195	0.003	0.002
US TREASURY 2012 1/8% 31/12/14 AU-2014 - RED. YIELD	1.991	0.261	0.078	0.156
US TREASURY 2012 2 3/4% 15/08/42 BONDS O - RED. YIELD	20.036	2.939	0.021	0.412
US TREASURY 2012 2 3/4% 15/11/42 BONDS O - RED. YIELD	20.266	2.951	0.000	0.000
US TREASURY 2012 2% 15/02/22 B-2022 - RED. YIELD	8.339	1.608	0.358	2.982
US TREASURY 2012 3 1/8% 15/02/42 BONDS O - RED. YIELD	19.335	2.910	0.091	1.758
US TREASURY 2012 3% 15/05/42 BONDS O - RED. YIELD	19.726	2.925	0.050	0.992
US TREASURY 2012 3/4% 30/06/17 AA-2017 - RED. YIELD	4.427	0.624	0.063	0.279
US TREASURY 2012 3/4% 31/10/17 AE-2017 - RED. YIELD	4.746	0.689	0.044	0.209
US TREASURY 2012 3/4% 31/12/17 AG-2017 - RED. YIELD	4.913	0.730	0.027	0.134
US TREASURY 2012 3/8% 15/03/15 S - RED. YIELD	2.188	0.284	0.083	0.182
US TREASURY 2012 3/8% 15/04/15 S - RED. YIELD	2.272	0.296	0.083	0.189
US TREASURY 2012 3/8% 15/06/15 S - RED. YIELD	2.439	0.310	0.093	0.228
US TREASURY 2012 3/8% 15/11/15 AF-2015 - RED. YIELD	2.848	0.344	0.117	0.334
US TREASURY 2012 5/8% 30/09/17 AD-2017 - RED. YIELD	4.674	0.605	0.117	0.548
US TREASURY 2012 5/8% 30/11/17 AF-2017 - RED. YIELD	4.841	0.704	0.043	0.207
US TREASURY 2012 5/8% 31/05/17 Z-2017 - RED. YIELD	4.355	0.602	0.075	0.325
US TREASURY 2012 5/8% 31/08/17 AC-2017 - RED. YIELD	4.598	0.651	0.061	0.280
US TREASURY 2012 7/8% 28/02/17 V-2017 - RED. YIELD	4.082	0.563	0.075	0.305
US TREASURY 2012 7/8% 30/04/17 Y-2017 - RED. YIELD	4.249	0.592	0.070	0.298

US TREASURY 2012 7/8% 31/01/17 U-2017 - RED. YIELD	4.005	0.550	0.077	0.309
US TREASURY 2012 7/8% 31/07/19 N-2019 - RED. YIELD	6.386	1.085	0.116	0.739
US TREASURY 2012 7/8% 31/12/16 AF-2016 - RED. YIELD	3.937	0.531	0.086	0.340
AVERAGE	4.870	0.822	0.128	1.055
D-peak, maximum d_m	10.553		0.675	
D-star				8.260

Appendix 3C: The Affine Term Structure Model

Estimation of an affine term structure model follows Cieslak and Povala (2014). The parameters of the following state-space representation are estimated using maximum likelihood based on the Kalman filter. The state equation is a first-order Gaussian VAR:

$$z_{t+1} = \Phi z_t + \Omega^{1/2}\varepsilon_t, \;\; where \;\; \varepsilon_{t+1} \sim NID(0, I_k)$$

where the state variables are four unobservable term structure factors labelled z_t, Φ is a 4 × 4 autoregressive matrix and Ω is a 4 × 4 matrix.

The stochastic discount factor is log-normally distributed of the form:

$$M_{t+1} = \exp\left(-r_t - \frac{\Lambda_t'\Lambda_t}{2} - \Lambda_t'\varepsilon_{t+1}\right)$$

where the risk-free interest rate (r_t) and the 'price of risk' (Λ_t) are affine in the state variables:

$$r_t = r + \gamma' z_t$$

$$\Lambda_t = \lambda + \beta z_t$$

The measurement equation in the n-period zero coupon yield is:

$$s_t^n = -\frac{lnP_t^n}{n} = -\frac{A_n}{n} - \frac{B_n'}{n} z_t + v_t^n \;, \;\; where \; v_t^n \sim NID(0, \mathrm{H})$$

Where bond prices are also affine functions of the state factors:

$$lnP_t^n = A_n + B_n' z_t$$

And where the parameters A_n and B_n can be obtained from solutions to the recursive difference equations shown below:

$$A_n = -r + A_{n-1} - B'_{n-1}\Omega^{1/2}\lambda + \frac{B'_{n-1}\Omega B_{n-1}}{2}$$

$$B'_n = -\gamma' + B'_{n-1}\left(\Phi - \Omega^{1/2}\beta\right)$$

Table C1: Affine Model Parameter estimates

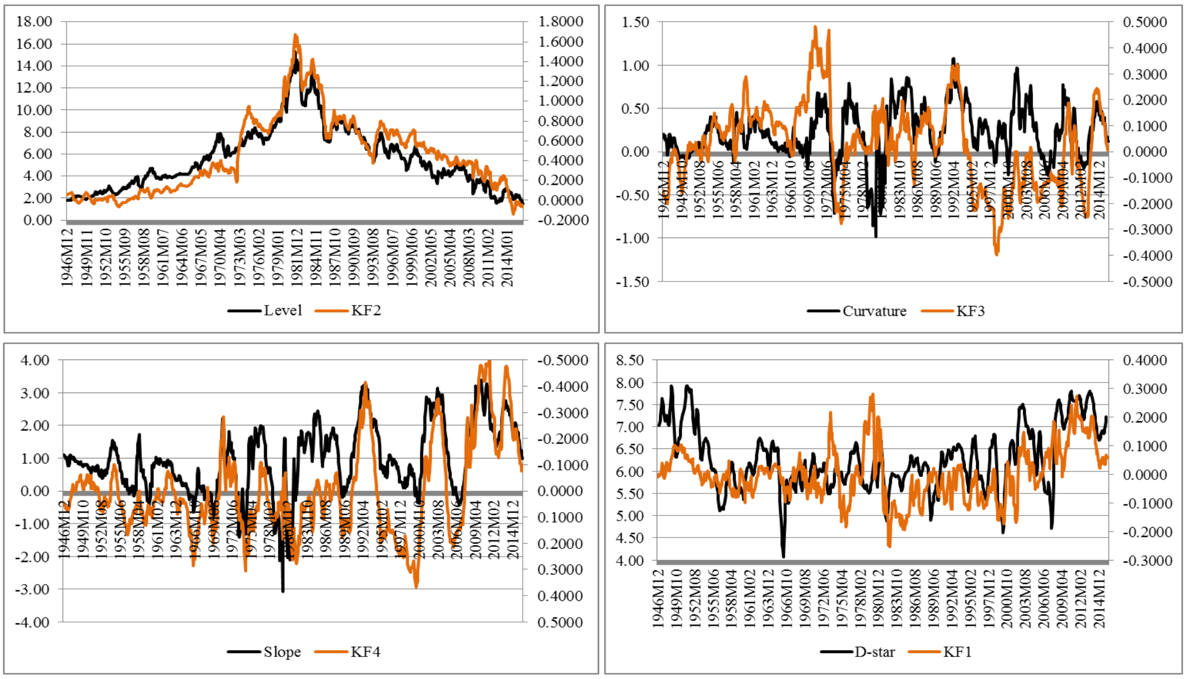
Φ matrix	*C1*	*C2*	*C3*	*C4*
R1	-0.01316	-	-	-
R2	-	-2.47404	-	-
R3	-	-	-0.18785	-
R4	-	-	-	-0.56723

	Value
R	0.01941
γ_1	0.008927
γ_2	0.025488
γ_3	0.012064
γ_4	0.014629
λ_1	0.274211
λ_2	-1.20668
λ_3	-1.09619
λ_4	0.804236
sigma	2.11E-07

The upper panel shows the estimated parameters in the diagonal 4 x 4 Φ matrix that enters in the state equation. The lower panel reports the other parameter estimates for the risk-free interest rate and price of risk equations. Sigma is the Kalman implied measurement error

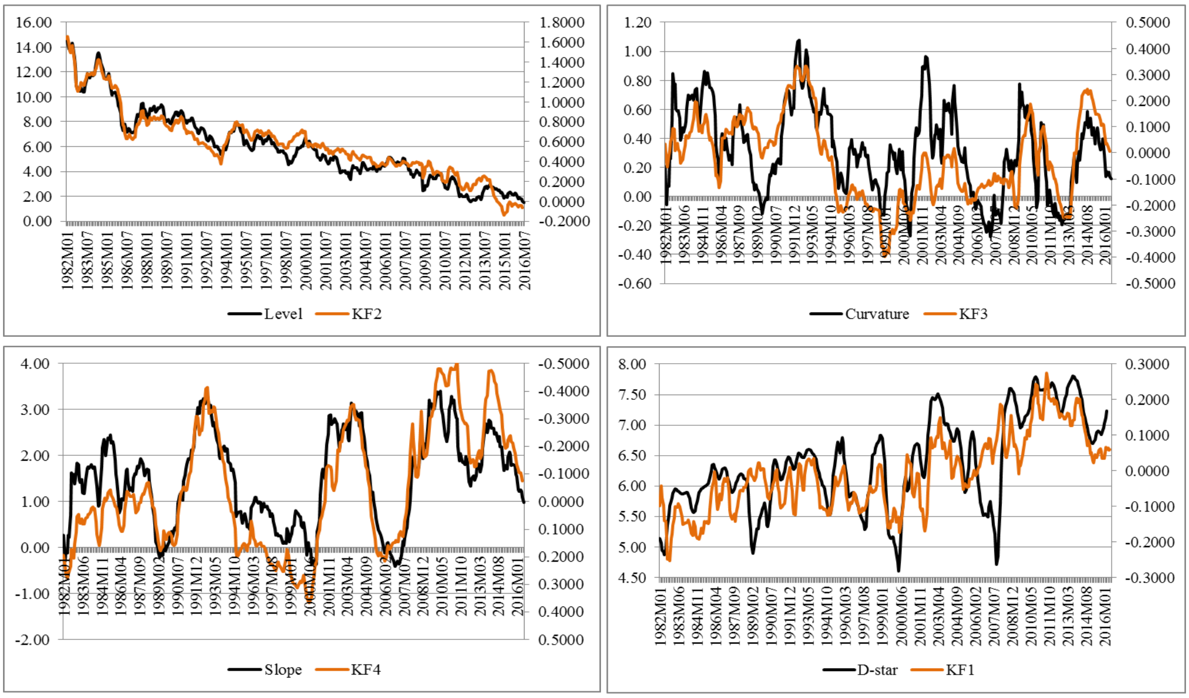
The model is estimated monthly over the 1946-2016 period using maximum likelihood. It is parsimonious, with only four parameters in the market price of risk and 13 parameters in total. The parameter estimates are reported in Table C1. The parameter matrix (Φ) is diagonal, which may allow the identification of the principal components. The four Kalman factors extracted from the model are shown in Figures C1 and, with more recent detail, in C2 alongside the four term structure factors – level, slope, convexity and position, i.e. D-star (D^*_t) based on cross-correlations. The third Kalman factor closely correlates with D-star (0.503, 0.728 1982-2016) and particularly over the period following *Volcker's Great Experiment* with high real US interest rates. The other three Kalman factors show significant correlations with the traditional level (0.940, 0.967 1982-2016); slope (-0.777, -0.871 1982-2016) and curvature (0.305, 0.633 1982-2016) measures.

Figure C1: Kalman Factors Aligned to Term Structure Parameters, 1946-2016 (Monthly)



The charts show, respectively, each of the four estimated Kalman factors aligned with four yield curve parameters – level, slope, convexity and position, i.e. D-star (D^{*}_{t}) – on the basis of correlation over the period 1946-2016. The third Kalman factor closely correlates (0.503) with D-star, with the other three showing significant correlations with the traditional level (0.940); slope (-0.777) and curvature (0.305) measures.

Figure C2: Kalman Factors Aligned to Term Structure Parameters, 1982-2016 (Monthly)



The charts show, respectively, each of the four estimated Kalman factors aligned with four yield curve parameters – level, slope, convexity and position, i.e. D-star (D^*_t) – on the basis of correlation over the period 1982-2016. The third Kalman factor closely correlates (0.729) with D-star, with the other three showing significant correlations with the traditional level (0.967); slope (-0.871) and curvature (0.633) measures.

Appendix 3D: US Treasury Yield Curve Methodology

The Treasury's yield curve is derived using a quasi-cubic hermite spline function. The inputs are the Close of Business (COB) bid yields for the on-the-run securities. Because the on-the-run securities typically trade close to par, those securities are designated as the knot points in the quasi-cubic hermite spline algorithm and the resulting yield curve is considered a par curve. However, the Treasury may input additional bid yields if there is no on-the-run security available for a given maturity range as they deem necessary for deriving a good fit for the quasi-cubic hermite spline curve. For example, they use composites of off-the-run bonds in the 20-year range reflecting market yields available in that time tranche. Prior to May 26, 2005, a rolled-down 10-year note with a remaining maturity nearest to 7 years was also used as an additional input. The current inputs are the most recently auctioned 4-, 13-, 26-, and 52-week bills, plus the most recently auctioned 2-, 3-, 5-, 7-, and 10-year notes and the most recently auctioned 30-year bond, plus the composite rate in the 20-year maturity range. The quotes for these securities are obtained at or near the 3:30 PM close each trading day. The inputs for the four bills are their bond equivalent yields.

Chapter 4

Using the New Yield Curve Parameter to Predict Future Financial Stress

4.1 Introduction

Identifying approaching periods of financial stress and forecasting future financial crises has not proved straightforward. This chapter proposes and tests a new measure of investors' *risk appetite*[34] extracted from the interest rate term structure and applied as a forward-looking indicator of shocks to the financial sector. These financial shocks form part of the so-called *risk-taking* policy transmission channel (see Adrian and Shin, 2010; Borio and Zhu, 2012, and Bruno and Shin, 2014). Recent experience warns that they pose significant adverse implications for the real economy. The unexpected bankruptcy of Lehman Brothers, for example, and the surprising near-failure of the American International Group (AIG) in 2008 had far-reaching effects on the international economy through falling asset prices and turmoil across key credit market spreads. The probability that financial instability leads on to macro-economic instability is known as "systemic risk." Many national policy-makers now have a formal mandate to avoid systemic risk and prevent financial instability from negatively affecting economic growth. In the United States, this role is established by the Dodd-Frank Wall Street Reform and Consumer Protection Act of 2009.

In the previous chapter, I argue that D-star implicitly measures the shape of the distribution of implied term premia across the interest rate term structure. These can provide additional information about the future path of macro-finance variables, such as the ISM index of US business activity and the high yield credit spread. This follows because the distribution of implied term premia indicates the excess demand for safe assets. Government bonds across different durations serve as safe assets for many investors and credit providers and these holdings of safe assets will likely correlate negatively with their risk appetite at each tenor. I define a safe asset as an instrument

[34] According to Gai and Vause (2006), risk appetite is determined by macroeconomic conditions and the risk aversion inherent in utility functions. This combines with measures of asset riskiness to generate risk premia.

that offers liquidity, stability of value, use as collateral, immunization[35] and low default risk (see also IMF, 2012). The canonical safe asset is the 10-year Treasury note[36], but the list includes all assets that are used in an information-insensitive fashion (Gorton et al, 2012). Their supply is not perfectly elastic. Supply shortages of safe assets can occur because of regulation, Central Bank LSAP, credit rating agency downgrades and falls in investors' risk appetite. Based on Walras' Law, shortages in the supply of safe assets can lead to macroeconomic disequilibria and greater financial stress (Caballero, 2006). Policy-makers are alert to the threat to the global financial system of a structural shortage of these safe assets (IMF, 2012). Their fears seem well-founded, since Krishnamurthy and Vissing-Jorgensen (2013) show empirically that the decreasing supplies of US Treasuries raise the probability of financial crises.

In Chapter 3, I adapt the Greenwood, Hanson and Stein (2010) *preferred habitat* model[37] to show that D-star may help to identify the changing sentiment of investors. In other words, when D-star extends (retracts), it indicates risk-seeking (risk-avoiding) investor behaviour and a lengthening (shortening) of their investment time horizons. This follows from the fact that a greater curvature of the term structure, at any given maturity, could derive from the lower term premia that are associated with an excess demand for safety at more distant tenors. I make use of the fact that there is a related distribution of implied forward rates behind the distribution of spot rates, each of which, in turn, is made up from a short-period policy rate component and a term premium. Although D-star captures the pattern of these expected policy rates and term premia across tenors, it does not necessarily correlate with their average size, because these levels are unrelated to the point where the term structure has the largest curvature. I acknowledge that these changes to curvature could also reflect fluctuations in investors' demand for Treasuries from a duration effect, following a fall in interest rate expectations, and from the recognition of a larger implied option value given greater interest rate volatility (Ilmanen, 1995). Yet, all three reasons are synonymous with more uncertain times and often with economic recessions. Thus, falls in D-star may indicate an excess demand for safe assets at longer time horizons and so warn of upcoming

[35] The ability to match the duration of liabilities.
[36] Safety is measured relative to the profile of expected liabilities. See Chapter 2. For example, I consider a risk-seeking investor as a long-term fund that moves away from a duration targeted position in, say, 10-year Treasuries and into equities or real assets, rather than an investor moving from cash into 10-year notes.
[37] This, in turn, is influenced by Vayanos and Vila (2009)

financial stress. This motivates a key research question: does the implied distribution of these expected policy rates and term premia and, hence, D-star matter for financial stability and for the future path of the economy?

The following sections first describe the benchmark risk data and then outline four different types of tests between D-star and the above list of macro-finance variables: Section 4.2 explains the financial stress and risk appetite data series. Section 4.3 considers Granger causality, compared to the slope and curvature factor alternatives. Section 4.4 focuses on BIC comparisons over different future horizons, against various benchmark alternatives. Section 4.5 reports two out-of-sample tests. The following Section 4.6 examines whether D-star offers any insight into the Y2K Bubble period and the 2007/08 Global Financial Crisis. Section 4.7 concludes.

4.2 Financial Stress Indexes and Risk Appetite Data

Financial regulators are incorporating demands for such forward-looking risk measures into new legislation, such as the European Union's UCITS IV (Undertakings for Collective Investment in Transferable Securities) Directive and AIFMD (Alternative Investment Fund Managers Directive). Yet, financial stress cannot be quantified in the same way as many other economic indicators (e.g., industrial output and employment), which count tangible objects. This has encouraged economists to develop new statistical indicators designed to provide a continuous signal of general financial stability. These indicators are collectively termed *financial stress indexes* (FSIs). They try to capture, among other things, the liquidity across financial markets and they may help to forecast potential changes in real economic conditions. FSIs frequently measure the underlying behaviour of investors from price volatility and risk premia data across several assets and they are often built using sophisticated statistical techniques. In the USA, official FSIs are regularly published by the Chicago, Cleveland[38], Kansas and St Louis Federal Reserve districts. For example, the Kansas Federal Reserve's monthly FSI comprises normalised measures of credit spreads (e.g. TED, 2-year swap spread, quality and high yield credit spreads) and market volatility (e.g. VIX, volatility of bank share price returns, correlation between equities and bonds). Similarly, the Chicago Federal

[38] Publication of the Cleveland FSI was temporarily 'suspended' in May 2016 for refinement and recalibration.

Reserve's *National Financial Conditions Index* (CFFCI) is a higher frequency, weekly measure of US financing conditions in money markets, debt and equity markets and the traditional and 'shadow' banking systems. It comprises a weighted average of 105 measures of financial activity, covering spreads, asset prices, volatility, liquidity ratios and opinion surveys, each expressed relative to their sample averages and scaled by their sample standard deviations. Consequently, FSIs are typically expressed as N(0,1) z-scores. These indexes are likely to move pro-cyclically with investors' risk aversion and with asset market riskiness. (see Hakkio and Keeton, 2009 and Kliesen, Owyang and Vermann, 2012). However, a major practical limitation is that FSIs remain barometers of current financial market stress that largely change contemporaneously with events. This provides added motivation to test my alternative approach to detect risk-avoiding behaviour at an earlier stage and so help to warn in advance of upcoming deteriorations in FSIs.

I use monthly estimates of D-star, taken from the US Treasury term structure (1954-2016) and investigate whether they can warn of upcoming periods of financial market stress. The construction of D-star in Chapter 3 recommends a 6-month centred moving average[39] and, so, the following tests all begin, at least, 3-months forward. When a low D-star reading reflects an excess demand for safe Treasury assets, this should indicate risk-avoiding behaviour by investors and credit providers. This may be confirmed by broader measures of risk appetite (e.g. investor surveys). As Treasuries are bid away from the money market, the collateral pool diminishes, which, in turn, leads to declines in repo activity. Correspondingly, credit providers may become more cautious and tighten financial conditions. This results in greater market volatility (e.g. VIX and MOVE), widening credit spreads (e.g. B less Baa/ BBB[40]) as default risks rise, and, hence, to increases in published *financial stress indexes*. To the extent that tighter financial conditions and diminished risk appetites cause investment time horizons to shorten and capital spending to decline, the real economy will subsequently weaken and measures of consumer and business confidence will deteriorate. I check the robustness of D-star as a predictor by monitoring the underlying macro-finance variables that describe this transmission process: (1) major financial stress indexes (e.g. the Kansas Fed FSI and the first principal component of all current Fed FSIs); (2) the key sub-

[39] This is to reduce measurement error, but it also correlates closely with the Kalman estimate at this frequency.
[40] BBB is the S&P equivalent to Moody's Baa investment grade rating

components of these FSIs (e.g. the 'quality' spread BBB-AAA grade; the 'high yield' spread B-BBB and the 'junk' spread CCC-B; the Merrill Lynch MOVE index of bond volatility; the CBOE VIX index of US equity volatility; US Treasury term premia estimates (Adrian et al, 2014)); (3) well-known indexes of economic activity (e.g. the US ISM and Philadelphia Fed indexes of manufacturing activity, University of Michigan consumer sentiment survey), which are likely affected later in the transmission process by adverse financial shocks, and (4) measures of investors' risk appetite (e.g. the ECB global risk aversion indicator; the variance-based risk aversion component of the VIX and the *CrossBorder Capital* Risk Appetite series). Each of these latter three data series represents a different way to measure risk appetite: the first is asset price or yield spread-based; the second extracts information from implied volatility data and the third represents investors' actual allocation decisions. The variance-based risk aversion[41] is calculated after expected stock market volatility has been removed from the CBOE VIX index (see Bekaert, Hoerova and Lo Duca, 2013). The *ECB global risk aversion index* comprises the first principal component of five widely-used, independent, but *ex post* risk appetite indicators, namely the *Commerzbank Global Risk Perception*, the *UBS FX Risk Index*, *Westpac's Risk Appetite Index*, the *BoA/ ML Risk Aversion Indicator* and the *Credit Suisse Risk Appetite Index*. *CrossBorder Capital's World Risk Appetite Index* measures the normalised deviations in actual asset allocation between risky (i.e. equities and corporate debt) and safe assets (i.e. cash and Treasuries). The ECB and CrossBorder Capital (www.liquidity.com) data series are available from their respective websites. All other data series were downloaded from the FRED database.

4.3 Granger Causality Tests

This section reports the results from a series of bi-variant tests, taken over different horizons of three months through 18-months that compare the efficacy of D-star – the position of the yield curve hump – in Granger causing the macro-finance variables described in Section 4.2. Two popular yield curve parameters are used as benchmark regressors against which to compare D-star: the slope of the US Treasury term structure

[41] Variance risk premium(t)=$VIX_t^2 – E_t(\sigma_{t+1}^2)$, where σ_t is the realised return volatility on the S&P500 over 22 days

– measured by the 10-year less 1-year Treasury yield spread – and its curvature – measured by the 1-5-10 year Treasury butterfly spread. I select a common monthly sample period covering 1990-2016, because this span embraces most of the data available for the selected series. Table 7 summarises the results. More detailed statistical tests are shown later in Tables A1-A13 in Appendix 4A. Across the thirteen series tested, the D-star variable demonstrates substantial Granger causality. The columns reported in the table indicate: (a) whether Granger causality between 12-18 months ahead is statistically significant at the 5% level; (b) whether or not this causation is one-way; (c) although necessarily partly subjective, whether the D-star results are stronger than those obtained from using the other yield curve parameters, and (d) whether these conclusions carry over to a longer sample, when available.

Taken overall, I cannot reject the hypothesis that D-star one-way Granger causes the financial stress indexes (FSIs) and their key components, and it seems to outperform the slope and curvature alternatives. D-star also appears to one-way Granger causes the US ISM and Philadelphia Fed business activity indexes and the 12-month change in the University of Michigan consumer sentiment survey, across both their shorter and longer sample periods. In contrast, the slope and curvature factors, for the most part, indicate either two-way causality or one-way reverse causality. An exception occurs with the Philadelphia Fed index over the shorter sample period, where both curvature and slope show evidence of one-way Granger causality at the 12-month and 18-month horizons. D-star also appears to Granger cause corporate credit spreads and both bond and equity volatility, key components of the FSIs. The US corporate 'quality' credit spread is defined as the Bank of America/ Merrill Lynch BBB less AAA rated corporate bond yields. The data show evidence that D-star one-way Granger causes this yield spread around 18 months ahead over both the 1970-2016 period and the shorter 1990-2016 period. There is evidence of two-way causality for the yield curve and curvature factors over the longer sample, but they show little evidence of any causality in the recent 1990-2016 period.

Table 7: Granger Causality Tests – Summary Results

Indicator	Significant GC 12-18 months	One-way GC	Outperforms Other YC Parameters	Robustness Check Over Longer Sample
PC1 FSI	√	√	√	
Kansas Fed FSI	√	√	√	
Quality Credit Spread BBB-AAA	√	√	√	√
High Yield Spread B-BBB	√	√	√	
Junk Credit Spread CCC-B	√	√	√	
MOVE Index	√	√	√	
VIX Index	√	√	√/o	
US ISM	√	√	√	√
Philadelphia Fed Index	√	√	√	√
U of M Consumer Sentiment(12m ch)	√	√	√	√
ECB Global Risk Aversion	√	x	√/o	
Risk Aversion	√	√	√/o	
CBC Risk Appetite	√	x	√/o	√/o

Comment: US ISM is the Institute of Supply Management national index of US manufacturing activity; Philadelphia Fed Index is a regional index of manufacturing activity; U of M Consumer Sentiment is the 12 month change in the University of Michigan survey; the Quality, High Yield and Junk Yield Spreads are credit spreads; the MOVE index is the Merrill Lynch measure of US bond market volatility; VIX is the CBOE measure of US equity volatility; Risk Aversion is a variance-based measure derived from the VIX; ECB Global Risk Aversion is a composite index derived from other vendors summarising global risk aversion; CBC Risk Appetite refers to the CrossBorder Capital index based on actual asset holdings; Kansas Fed FSI is the financial stress index published by the Kansas Federal Reserve, and PC1 FCI is the first principal component of all published financial stress indexes by regional Federal Reserve districts. A √ denotes a positive; x denotes a negative and √/o signifies 'at least as good as'. GC denotes Granger causality.

The data show evidence of one-way Granger causality of D-star on the 'high yield' spread (single B less BBB) over all horizons during both sample periods. There is some evidence of two-way causality for the yield curve slope and curvature factors and evidence of one-way reverse causality from the high yield spread on to the yield curve

(1990-2016) and curvature (1970-2016). The results for the 'junk' credit market (CCC less single B) show evidence of one-way Granger causality of D-star over all horizons. There is some suggestion of one-way reverse causality from the high yield spread on to the yield curve and curvature. There is evidence of one-way Granger causality of D-star on the Merrill Lynch MOVE index of bond volatility at the 18-month horizon. Similarly, the data again suggest one-way reverse causality for the MOVE index on to the slope and curvature factors. The impact of D-star on equity market volatility is measured using the CBOE VIX index. D-star and the curvature factor both show one-way Granger causality at the 12-month and 18-month horizons. The slope factor reveals evidence of reverse causality.

I found no significant Granger causality in the variance-based risk aversion data, apart from the slope and D-star factors at the 18-month horizon. There is more compelling evidence that D-star Granger causes the overall FSIs, the CBC Risk Appetite series (two-way and in shorter sample) and the ECB global risk aversion data at six through 18-month horizons. The data show mostly reverse causality for the slope factor and give only some evidence of Granger causality for the curvature factor at 12-months and 18-months in the ECB global risk aversion case. In summary, the results from these Granger causality tests are encouraging for the D-star factor; mixed for the curvature factor and disappointing for the slope factor.

4.4 Testing Prediction Using Bayesian Information Criteria

This section employs further statistical tests to evaluate the economic and statistical importance of D-star as a predictor. I revert to individual data spans, widen the range of alternative regressors and adopt a different testing methodology, using Bayesian Information Criteria (BIC) to discriminate between: (a) a benchmark model that predicts a target, e.g. FSI and US economic activity, using the first three principal components (PCs) of the Treasury term structure as regressors, and (b) a second model that includes D-star. For completeness, D-star is also tested alone in order to establish nested test results. This approach differs from testing for Granger causality. While the results tell us little about exogeneity, they allow the signs and strength of the coefficient loadings to be checked for plausibility. In each case, I use monthly data, looking from three months to two years ahead to further assess robustness. The BIC tests are applied to the same set of macro-finance variables described in Section 4.1.

Table 8: Regression of First Principal Component of Major US National Financial Stress Indexes on Principal Components of the US Treasury Yield Curve, with and without D-star, for various lead-times (3, 6, 9, 12, 15 and 18 months), 1994-2016 (Monthly)

	3m	6m	9m	12m	15m	18m
BIC	3.850	3.846	3.806	3.735	3.658	3.559
BIC (+D-star)	3.866	3.847	3.677	3.298	3.234	3.337
BIC (D-star)	3.852	3.825	3.742	3.575	3.454	3.442
R^2	0.050	0.054	0.091	0.153	0.216	0.289
R^2 (+D-star)	0.054	0.071	0.217	0.464	0.497	0.443
R^2 (D-star)	0.007	0.034	0.111	0.247	0.333	0.341
D-star (se)	-0.175 (0.125)	-0.379*** (0.124)	-0.689*** (0.119)	-1.032*** (0.110)	-1.199*** (0.103)	-1.214*** (0.103)

Comment: BIC refers to the Bayesian Information Criteria reported for different time horizons from 3 months to 18 months. The default reading shown is for the benchmark regression. A +D-star in brackets denotes the same regression, but including D-star as a second regressor. A D-star in brackets refers to the regression without the benchmark variable. The same applies to the R^2 statistic. The D-star line reports estimated loadings on the D-star variable in the joint regression. se denotes the Newey-West adjusted standard error. One, two and three asterisks signify significance at the 10%, 5% and 1% levels.

Where appropriate, I also test two alternative benchmarks by substituting the Chicago Federal Reserve's *National Financial Conditions Index* (CFFCI) and estimates of the US Treasury term premia (Adrian et al, 2014) in place of the principal components benchmark. Although the CFFCI is available for a shorter period than the PCs, it is a broadly-based basket of key financial variables, as previously described. The regression models take the form:

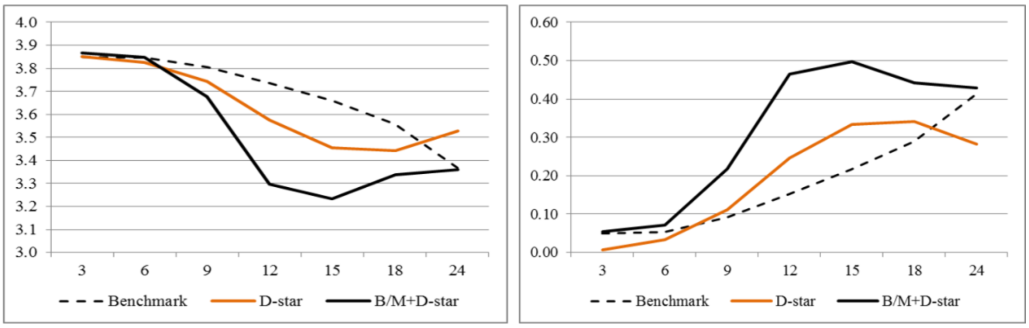
$$Y_{t+k} = \alpha + \sum_i \beta_i \, PC_{i,t} + \gamma D_t^* + \varepsilon_t \qquad (5)$$

where Y_{t+k} is the predicted factor k periods ahead, e.g. the ISM index of US manufacturing business activity; $PC_{i,t}$ represent the first three principal components of the US Treasury yield curve; D^*_t is D-star$_{av}$ in period t, and ε_t is a random error term. α,

β_i and γ are parameters to be estimated. The same structure is adopted for all predicted variables. The estimation uses the available monthly data over the period. The time horizon k takes the values 3, 6, 9, 12, 15, 18 and 24 months.

Figure 10: First Principal Component of Major Financial Stress Indexes (FSIs), 1994-2016 (Monthly)

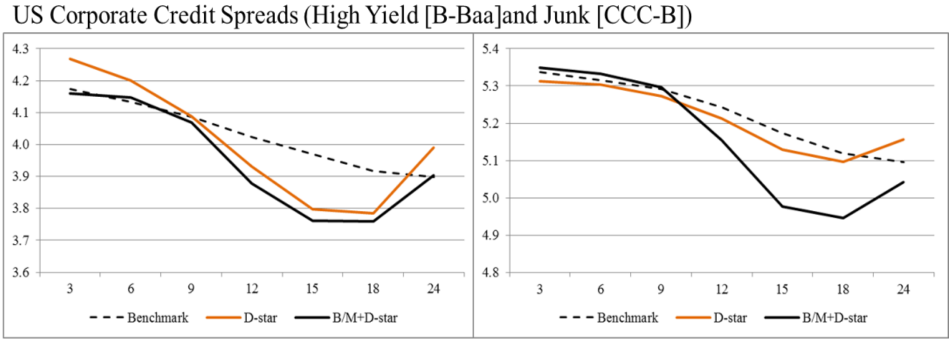
First PC of Major FSIs (3x YC PCs): BICs [left] and R^2 [right]



Comment: BIC refers to the Bayesian Information Criteria reported for different time horizons from 3 months to 24 months. B/M+D-star denotes the regression, but including D-star as a second regressor. D-star refers to the regression without the benchmark variable. The same applies to the R^2 statistic.

Table 8 reports the BIC and R^2 results and loadings on D-star for regressions using the first principal component of the US National FSIs. Three sets of BIC results are shown, with and without D-star. The BIC values for the benchmark decline smoothly as the forecast horizon extends. The inclusion of D-star noticeably lowers the BIC values over the 9-18 month horizons, with its major impact felt at 15 months, where D-star has a significant negative loading. According to the coefficient, the FSI is reduced by 1.2 standard deviations for each additional year that the investment horizon extends. At the 15 month horizon, the R^2 of the regression is 0.497. The importance of D-star can be seen from a simple two-variable regression with the FSI. D-star actually outperforms the benchmark, over the 6-18 month horizon, and its inclusion significantly improves the BICs and R^2 statistics. This result is shown graphically in Figure 10. Here, the broken lines depict the respective benchmarks and the solid lines show the results for D-star alone (orange) and for the benchmark with D-star included (black).

Figure 11: US Corporate Spreads, 1987-2016 (Monthly)

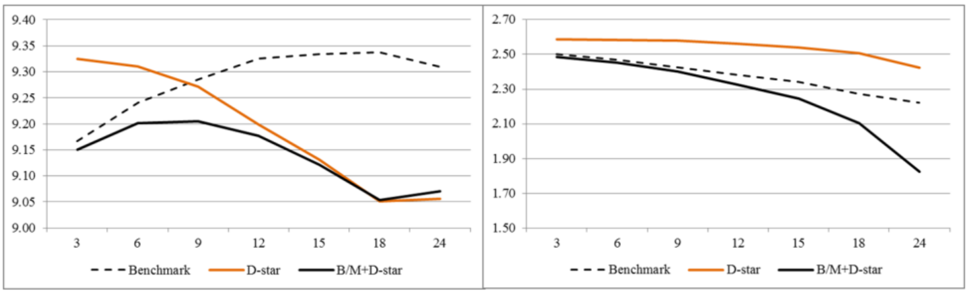


Comment: 3x YC PCs denote the first three principal components of the Treasury yield curve using in the benchmark regression. BIC refers to the Bayesian Information Criteria reported for different time horizons from 3 months to 24 months. B/M+D-star denotes the regression, but including D-star as a second regressor. D-star refers to the regression without the benchmark variable. High yield (B-BBB or Baa) and Junk (CCC-B) refer to yield spreads between bonds of different credit quality

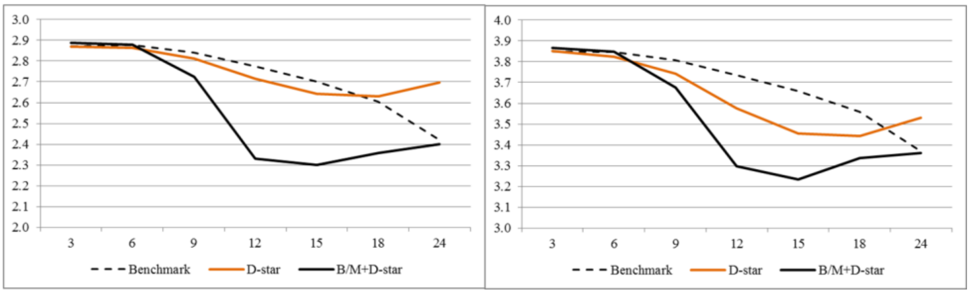
Figures 11 and 12 cross-check the robustness of this result by splitting-out and re-testing some of the key sub-components of the FSIs – credit spreads, bond volatility and term premia – and by comparing one of the published FSIs – the Kansas FSI – alone (i.e. not in principal component form). Figure 11 reports the results for the US High Yield (B less Baa/ BBB) and Junk (CCC less B) corporate credit spreads. The efficacy of D-star as a predictor can be seen in both cases, again around the 15-to-18 month horizon. The upper panel in Figure 12 reports the results for the MOVE index of bond volatility and for the US Treasury average term premia taken across the yield curve (Adrian et al, 2014). The lower panel compares the result for the Kansas FSI (left) with the first principal component of all FSIs. D-star appears to have a major negative effect on future bond volatility. The sign of the loading on D-star suggests that as investment horizons lengthen, so volatility progressively subsides. Term premia show a similar, but less emphatic result. Taken overall, falls in D-star appear to raise Treasury prices and increase bond market volatility 18-24 months ahead. Next, corporate credit spreads subsequently widen out 15-18 months ahead, so reinforcing the impact on FSIs.

Figure 12: Financial Stress Indexes (FSIs) and Bond Risks, 1994-2016 (Monthly)

Bond Risks (MOVE and Average Nominal Term Premia)



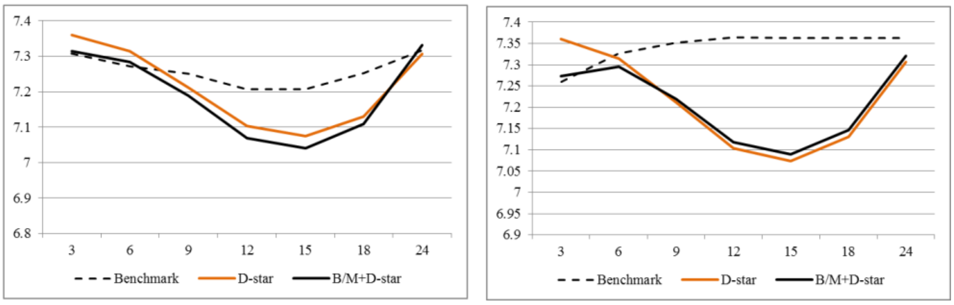
Financial Stress (Kansas Fed Index and 1st PC of Major FSIs)



Comment: 3x YC PCs denote the first three principal components of the Treasury yield curve using in the benchmark regression. BIC refers to the Bayesian Information Criteria reported for different time horizons from 3 months to 24 months. B/M+D-star denotes the regression, but including D-star as a second regressor. D-star refers to the regression without the benchmark variable. FSIs describe financial stress indexes. MOVE is the Merrill Lynch index of bond volatility. US Treasury term premia are averages across the yield curve.

Figure 13: University of Michigan US Consumer Sentiment Survey, 1985-2016 (Monthly)

12 month Change in US Consumer Sentiment (3x YC PCs and CFFCI)

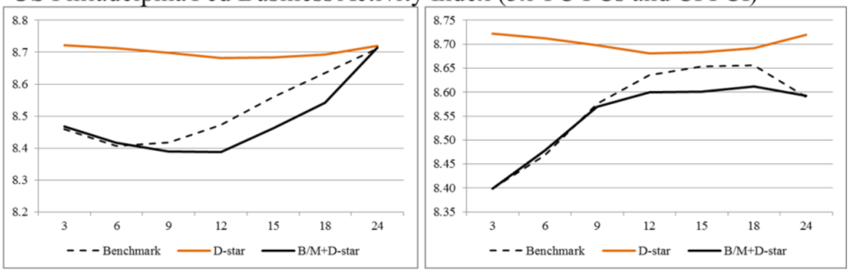


Comment: US Consumer Sentiment is the University of Michigan monthly survey of consumer attitudes. 3x YC PCs refers to the first three principal components of the Treasury yield curve. CFFCI is the Chicago Federal Reserve National Financial Conditions Index. BIC refers to the Bayesian Information Criteria reported for different time horizons from 3 months to 24 months. B/M+D-star denotes the regression, but including D-star as a second regressor. D-star refers to the regression without the benchmark variable.

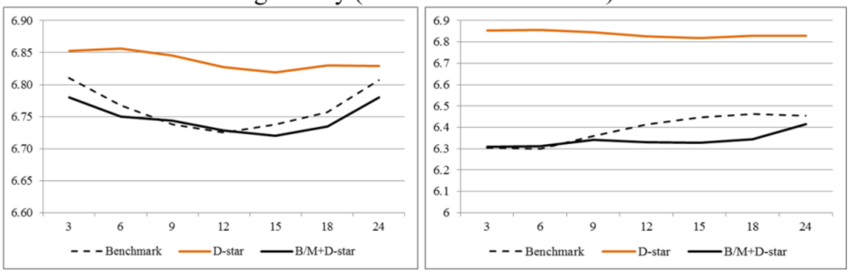
I extend these results to the other macro-finance variables listed in Section 4.1. They generally show that the inclusion of D-star improves prediction. Moreover, the loadings on D-star seem plausible and they have the economically correct signs across each model. Figure 13 reports the BIC values for the 12 month change in the University of Michigan US Consumer Sentiment Survey, using the first three principal components of the Treasury yield curve (left-hand side) and the CFFCI (right-hand side). The introduction of D-star improves (i.e. reduces) the BIC statistic most around 15 months ahead, most noticeably for the CFFCI benchmark. A larger value of D-star leads to an increase in US consumer sentiment. A Bai-Perron test points to only one significant break-point in the regression model over the sample, which occurred just ahead of the recession in January 2001. For the two measures of US economic activity – the regional Philadelphia Federal Reserve's Manufacturing Activity Index and the national ISM Purchasing Managers' Index – their BIC values decrease around the 12-15 month future horizon when D-star is added. See Figure 14. Again a larger D-star value boosts economic activity, consistent with risk-seeking. The two upper charts report BIC results for the regional Philadelphia Fed activity index and the lower charts report the national ISM survey. The left-hand charts use the three yield curve factors (3x YC PCs) as their benchmark, while the right-hand charts introduce the Chicago Fed's National *Financial Conditions Index* (CFFCI) as a benchmark. Although the CFFCI already incorporates information from a large number of variables, D-star incrementally improves the regression.

Figure 14: US Business Activity, 1954-2016 (Monthly)

US Philadelphia Fed Business Activity Index (3x YC PCs and CFFCI)



US ISM Manufacturing Survey (3x YC PCs and CFFCI)

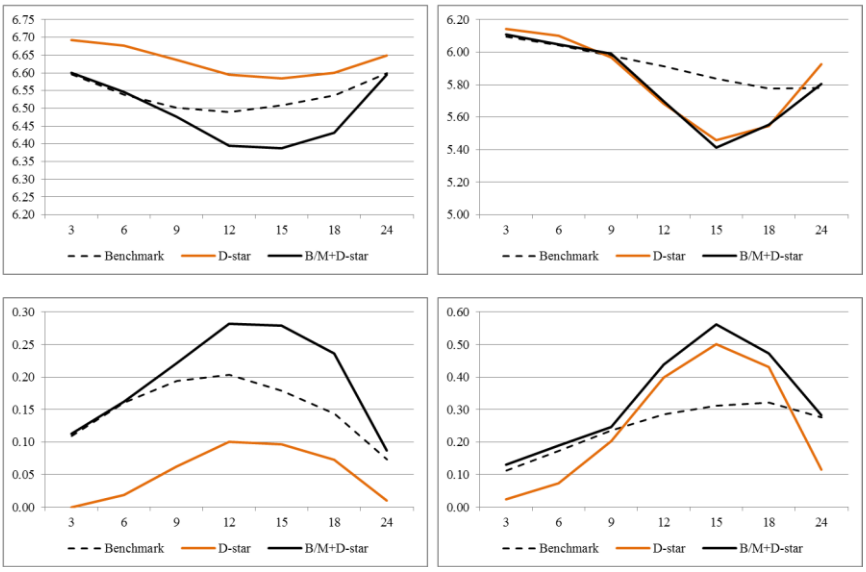


Comment: US Philadelphia Fed Business Activity Index and US ISM Manufacturing Survey are monthly barometers of US economic activity. 3x YC PCs refers to the first three principal components of the Treasury yield curve. CFFCI is the Chicago Federal Reserve National Financial Conditions Index. BIC refers to the Bayesian Information Criteria reported for different time horizons from 3 to 24 months. B/M+D-star denotes the regression with D-star as a second regressor. D-star refers to the regression without the benchmark variable.

Figure 15: USM Index 1954-2016 and 2000-2016 (Monthly)

US ISM Manufacturing Survey (3x YC PCs: 1954-2016 [left]& 2000-2016[right])

(BIC statistics 1st row, R^2 2nd row)



Comment: US ISM Manufacturing Survey is a monthly barometer of US economic activity. 3x YC PCs denote the first three principal components of the Treasury yield curve. BIC refers to the Bayesian Information Criteria reported for different time horizons from 3 months to 24 months. B/M+D-star denotes the regression, but including D-star as a second regressor. D-star refers to the regression without the benchmark variable. The same applies to the R^2 statistic. Two samples are reported: 1954-2016 (left) and 2000-16 (right).

Figure 16: BIC Tests on Risk Appetite Using Three Benchmarks, various time periods (LHS CFFCI, Middle 3xYC PCs, RHS Real Term Premia)

Row 1: ECB Risk Appetite; Row 2: Risk Aversion from VIX; Row 3 CBC World Investors' Risk Appetite

Source: Author's calculations and Federal Reserve; Comment: The chart reports the BIC for regressions that include and exclude, where stated, the D-star variable. The left-hand column of three charts uses a benchmark based on the Chicago Fed National Financial Conditions Index to predict three measures of risk appetite 3-to-24 months ahead: (a) ECB Global Risk Appetite (1996-2016); (b) Risk aversion from VIX variance premium (1984-2016) and (c) CBC World Investors' Risk Appetite (1978-2016). The middle and final columns do the same, but with different benchmarks based, respectively, on the first three principal components of the Treasury yield curve and the real US Treasury average term premia. The introduction of D-star adds information, notably to the first two rows, which, respectively, show the ECB's global appetite measure and a risk aversion measure based on the CBoE VIX index.

The charts in Figure 15 further test the robustness of D-star as a predictor of the ISM index by comparing two sample periods: 1954-2016 and the more recent 2000-2016. I use the principal components benchmark, because this offers the longer consistent history. The starting point for the more recent period is the new Millennium. Although it admittedly follows the late-1990s bubble period of inflated US asset prices, this period is deliberately chosen to evaluate the importance of D-star during the Global Financial Crisis and the Great Recession. The inclusion of D-star noticeably improves the BIC statistics for both periods, and, in fact, the relationship appears to strengthen during the latest years. For comparison, I also report R-squared statistics in the lower panels of Figure 15. These are not strictly comparable for the usual reasons, but they do offer a more intuitive measure of how the D-star variable performs: thus, it alone can explain almost half of the variation in the US ISM index over the 2000-2016 period. The loadings on the D-star factor (not shown) are significant at the 1% level for the 12, 15 and 18-month forward-looking periods and they attain a positive peak value of 6.91. This suggests that each one year change in D-star is consistent with around a 15% swing in the ISM manufacturing activity index. Both sets of results also indicate that the impact of D-star is felt some 15 months ahead. Moreover, these results seem stable according to a Bai-Perron break-point test: the longer data sample highlights only one significant breakpoint in March 1978 – a time of some turmoil in the US economy and Treasury market during the stagflation and weak US dollar years of the Carter Presidency.

Figure 16 tests the effect of D-star on three investor risk appetite measures: (1) the ECB's published measure (1996-2016); (2) the *variance premium* (1984-2016), and (3) the *CrossBorder Capital World Risk Appetite Index* (1978-2016). As a further robustness check, I also include a third benchmark (shown as the third column of charts) based on average US Treasury term premia, using data from Adrian et al. (2014), but normalised by US CPI inflation[42]. Again the evidence seems to show that the addition of D-star improves the BIC statistics for the ECB and variance-based measures of risk aversion at the 12-15 month horizon. For the CBC risk appetite series, the improvement

[42] The Adrian et al. (2014) data is not stationary and appears to be integrated of degree one. To eliminate the trend, I took an orthogonal regression between the published term premia series and the rolling three-year US CPI inflation rate.

is most evident at the shorter 9-month horizon. The results seem robust across each of the three benchmarks.

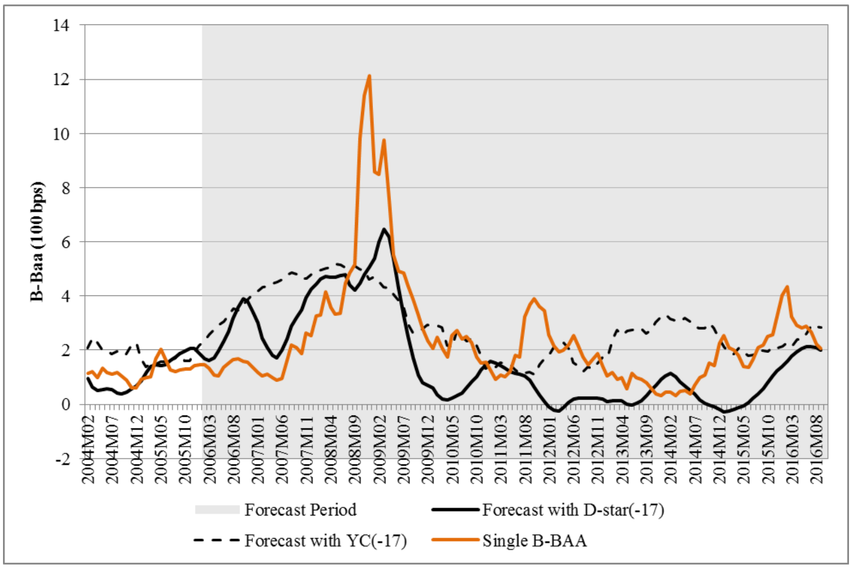
4.5 Out of Sample Tests

The results in Section 4.4 are all in-sample. In Figures 17 and 18, I use D-star to predict the US high yield credit spread (B-BBB) and the 12-month change in the University of Michigan US Consumer Sentiment Survey, out-of-sample. The justification for using credit spread data is that they correlate closely with financial stress indexes (0.882, with first PC), but they are available over a longer time span, starting in the late-1980s. Consumer sentiment is an example of widely-used economic data that is similarly available over a lengthy span. For both cases, an in-sample regression model was estimated using monthly data from 1987-2006. This found an optimal lead-time on D-star of 17 months for the credit spread and 14 months for the change in consumer sentiment. The regression parameters were applied to estimated values of D-star, advanced respectively by these lead-times, over the subsequent out-of-sample period 2007-2016 to predict the high yield spread and the change in consumer sentiment, and then to compare these results with the known outturns. The 10-1 year Treasury yield curve slope was incorporated into a similar regression model to benchmark both sets of results.

The D-star model appears to perform better in each test. Figures 17 and 18 display the respective results. For the period January 2007 to June 2009, which contains the Global Financial Crisis, the credit spread benchmark yield curve model had a MSE[43] of 2.99, compared to 2.45 for the D-star model. Over the same time-frame, the consumer sentiment benchmark yield curve model had a MSE of 14.03, compared to 12.17 for the D-star model.

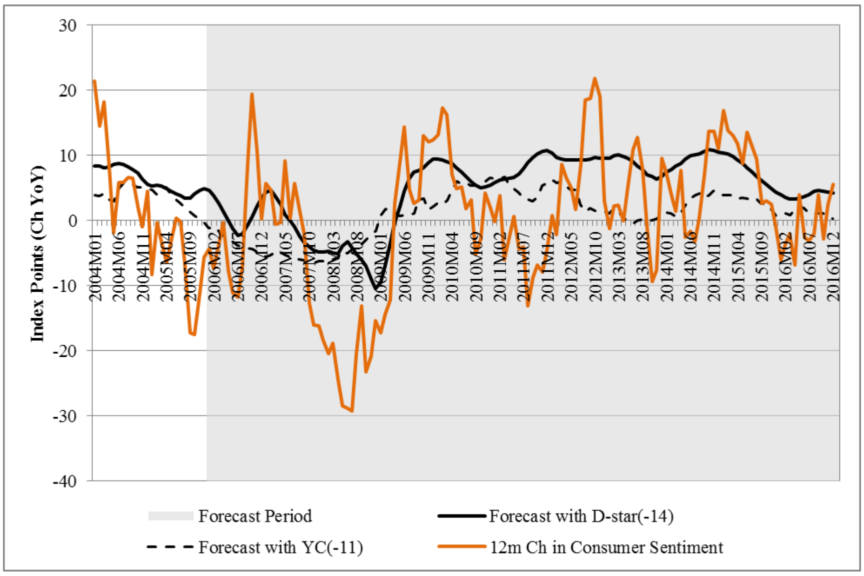
[43] MSE: mean-squared error

Figure 17: US High Yield Spread (B-BBB) – Actual and Out-of-Sample Forecasts, 2004-16 (Monthly)



Comment: The chart shows the out-of-sample results from two regression models used to predict the US high yield credit spread (B-BBB), using D-star (solid line) and the 10-1 year yield curve slope (broken line), with both lagged by a fixed 17 months. The models were estimated from 1987-2006 and used to predict forwards 2007-2016. The MSE of the D-star model is 2.45 and 2.99 for the yield curve model.

Figure 18: US Consumer Sentiment (University of Michigan) – Actual 12 month change and Out-of-Sample Forecasts, 2004-16 (Monthly)

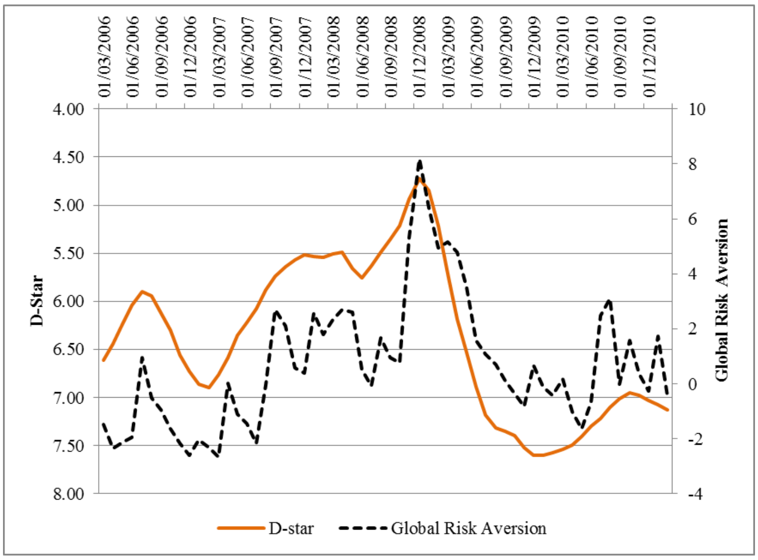


Comment: The chart shows the out-of-sample results from two regression models used to predict the 12 month change in US consumer sentiment, using D-star (solid line) and the 10-1 year yield curve slope (broken line). The models were estimated from 1987-2006 and used to predict forwards 2007-2016. The MSE of the D-star model is 12.17 and 14.03 for the yield curve model.

4.5 Event Studies – The Y2K Bubble and The Global Financial Crisis

The previous three sections suggest that movements in D-star generally pre-date subsequent movements in risk appetite, risk spreads and business activity around 12-15 months ahead. An alternative approach is to consider specific cases of financial turbulence and then test whether prior movements in D-star provide any forewarnings? For example, Figure 19 charts the ECB Global Risk Aversion measure[44], over the period of the 2007/08 Global Financial Crisis, with D-star advanced by 12 months and plotted inverted alongside. D-star seems to align with subsequent inflexion points in this risk aversion index and over the five year period the two series have a correlation coefficient of -0.507. In other words, contractions in D-star appear to warn of growing risk avoidance by investors, consistent with a decreased demand for risky assets and a heighted demand for safe assets that is subsequently confirmed by market action.

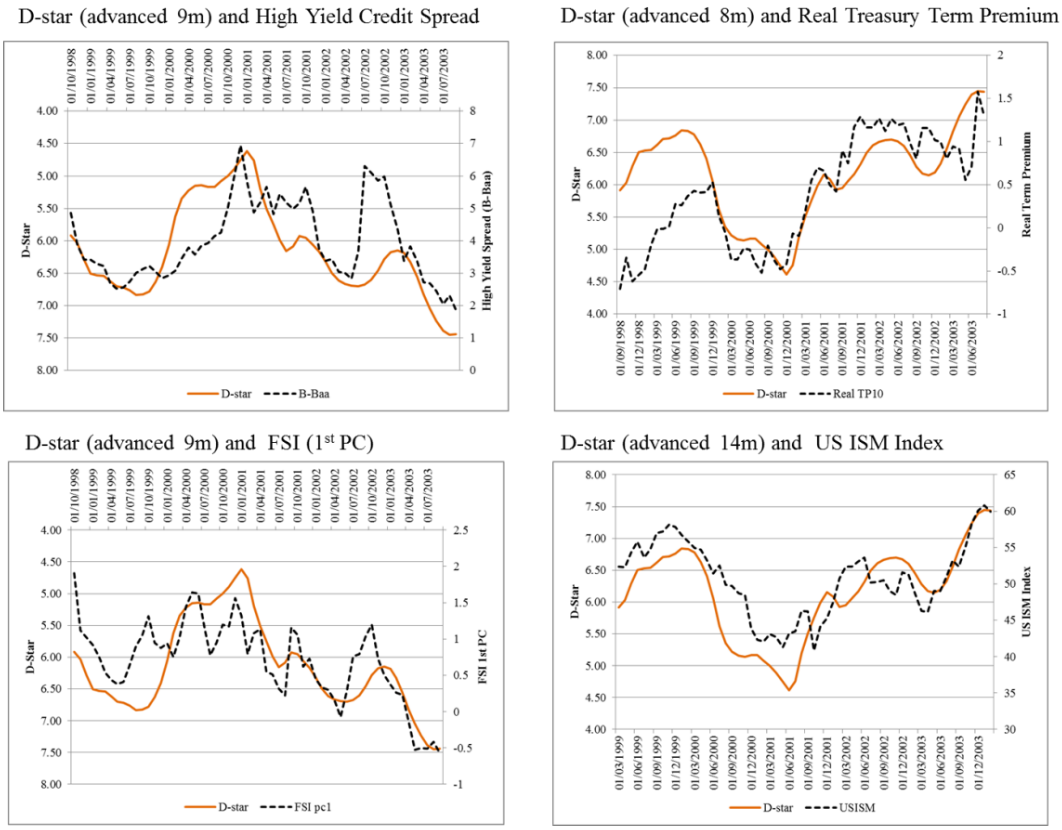
Figure 19: Global Risk Appetite (ECB Measure) and D-star (inverted, advanced 12 months), 2006-2010 (Monthly)



Comment: D-star measures the lateral position of the hump in the US Treasury yield curve along the maturity axis. The chart shows the co-movement between the ECB's Global Risk Aversion measure (broken line) and D-star (solid line). D-star has been advanced by 12-months and is shown inverted.

[44] ECB Risk Aversion series starts in 1999 during the 'Y2K Bubble' period, so the GFC is its first effective test.

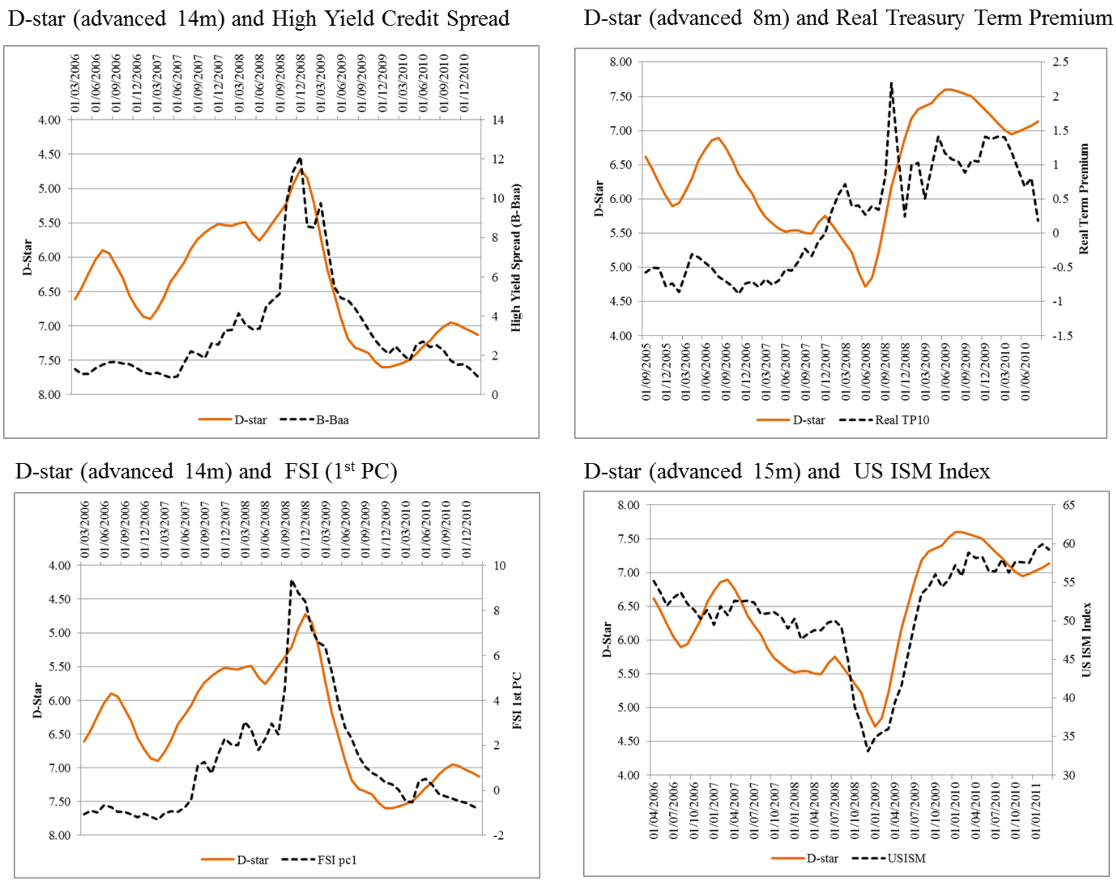
Figure 20: Y2K Bubble Finance Crisis – D-star (Advanced) and Selected Macro-Finance Variables, 1999-2003 (Monthly)



Comment: D-star measures the lateral position of the hump in the US Treasury yield curve along the maturity axis. It has been advanced by the number of months indicated to align with each of the other reference series in the chart panels. B-Baa refers to the corporate credit spread; 'real' TP10 is the nominal term premia of the 10-year US Treasury, with an inflation trend removed by orthogonal regression; FSI PC1 is the first principal component of published FSIs and USISM is the US purchasing managers' index of business activity. In the 1999/ 2000 Y2K period, D-star appears to lead the credit and financial markets by around 9 months and the real economy by some 12-15 months.

Figures 20 and 21 broaden this event study using some of the underlying drivers of the risk aversion data to analyse more deeply the 2007/08 Global Financial Crisis and also adding the Y2K Bubble period at the end of the 1990s decade as a further robustness check. They report the values of D-star, advanced appropriately, to best align (using simple correlation coefficient values for each period), respectively, with turning points in the following macro-finance variables: (a) single B less Baa/ BBB corporate credit spread; (b) average Treasury term premium (across maturities), adjusted by an inflation trend; (c) first principal component of major published FSIs, and (d) US ISM (Purchasing Managers') Index. The lead times vary, but, as before, they generally lie in the 9-15 month range. The lead times for the credit market and FSI are slightly longer in the recent GFC case study. Apart from the 10-year real term premia (0.600, 0.467), the correlations with D-star are similar across the two case studies: FSIs (-0.698, -0.634); high yield spreads (-0.594, -0.537) and ISMs (0.809, 0.818). [The first number in round brackets refers to the correlation coefficient in the Y2K event study and the second number to the GFC study.] The unusual spike in term premia during the GFC could be explained by the sudden and specific need for cash as the repo and interbank markets disappeared.

Figure 21: Global Finance Crisis – D-star (Advanced) and Selected Macro-Finance Variables, 2006-10 (Monthly)



Comment: D-star measures the lateral position of the hump in the US Treasury yield curve along the maturity axis. It has been advanced by the number of months indicated to align with each of the other reference series in the chart panels. B-Baa refers to the corporate credit spread; 'real' TP10 is the nominal term premia of the 10-year US Treasury, with an inflation trend removed by orthogonal regression; FSI PC1 is the first principal component of published FSIs and USISM is the US purchasing managers' index of business activity. In the 2007/08 GFC period, D-star appears to lead the credit and financial markets and the real economy by 12-15 months, but bond markets by significantly less.

The results suggest that as D-star extends (contracts), real Treasury term premia widen (narrow); high yield credit spreads narrow (widen); business activity increases (decreases) and financial stress indexes subside (rise). This interpretation is consistent with the intuition that D-star captures changes in investors' risk appetite. Moreover, it also indicates that safe and risky asset prices negatively correlate: as risk appetite improves bond term premia rise, thereby pushing down Treasury prices, alongside credit spreads tighten, so pushing up corporate bond prices in relative terms. The results from these two event studies are fully in line with the previous time-series analysis and seem to confirm the 12-15 month lead-time between D-star and the various macro-finance variables.

4.7 Conclusion

In this chapter, I try to show that D-star, a new yield curve parameter, contains information, beyond that obtained from the traditional and widely-used slope and curvature factors, that helps assess future financial risk, as summarised by published *financial stress indexes* (FSIs). D-star can be thought of as another measure of investors' risk appetite that implicitly reflects the underlying excess demand for safe asset Treasury bonds. Shocks to risk appetite operate through the *risk-taking* policy transmission channel. I consider four ways of testing the effectiveness of this transmission process. D-star performs robustly in all cases: (1) it comfortably beats the traditional yield curve measures of slope and curvature in terms of Granger causality across a broad range of economic and financial variables; (2) it lowers the BIC statistic at a similar 12-15 month ahead horizon for this same variable set, compared to various benchmarks; (3) when applied as a forward-looking indicator, it beats an OOS yield curve-based future predictor of both credit spreads and US consumer sentiment over 10-year horizons, and (4) according to event studies, it provides advance warnings of the Y2K and 2007/08 Crises. I have maintained the same pool of economic and financial variables throughout to avoid accusations of data-mining. These tests are broad, but they are not exhaustive and they provide no intuition as to why a 12-15 month time-scale seems to work. Notwithstanding, the results are sufficiently promising to suggest the monitoring of D-star and its possible inclusion in future FSIs.

Appendix: Granger Causality Test Results

(a) <u>Financial Stress Indexes (FSIs)</u>

Table A1: Granger Causality Tests – US FSI PC1, 1994-2016

1994-2016	3m	6m	12m	18m
D-star	0.4158	*0.0179*	*0.0047*	*0.0015*
	0.7830	0.9164	0.8702	0.7189
Slope	0.2856	0.6868	*0.0225*	0.1695
	0.0000	*0.0007*	*0.0004*	*0.0262*
Curvature	0.6687	0.8789	0.2760	0.3629
	0.1055	0.0909	*0.0058*	*0.0150*

P-values shown. 3m, 6m, etc denotes the lead-time used to test Granger causality. Italics indicate significance at 5% level. D-star is the position of peak curvature. Slope is the 10 year-1 year Treasury yield spread. Curvature is the 1-5-10 year Treasury butterfly spread. The first row for each variable measures Granger causality 'from' the factor 'to' the target, and the second row shows the reverse causality 'from' the target 'to' the factor. Comment: The data from these bi-variant tests show evidence of one-way Granger causality of D-star on the PC1 FSI index between 6-18 months over the 1990-2016 period. There is evidence of reverse one-way causality for the US FCI on to the slope and curvature factors.

Table A2: Granger Causality Tests – Kansas Fed FSI, 1990-2016

1990-2016	3m	6m	12m	18m
D-star	0.1610	*0.0271*	*0.0188*	*0.0012*
	0.7303	0.8008	0.7300	0.4594
Slope	0.0273	0.2854	0.0834	0.0885
	0.0000	*0.0001*	*0.0027*	*0.0140*
Curvature	0.1555	0.2919	0.1437	0.0570
	0.1428	0.3591	0.2712	0.2724

P-values shown. 3m, 6m, etc denotes the lead-time used to test Granger causality. Italics indicate significance at 5% level. D-star is the position of peak curvature. Slope is the 10 year-1 year Treasury yield spread. Curvature is the 1-5-10 year Treasury butterfly spread. The first row for each variable measures Granger causality 'from' the factor 'to' the target, and the second row shows the reverse causality 'from' the target 'to' the factor. Comment: The data from these bi-variant tests show evidence of one-way Granger causality of D-star on the Kansas FSI index between 6-18 months over the 1990-2016 period. There is evidence of reverse one-way causality for the US FCI on to the slope factor. Curvature gives no signal either way.

(b) Key Components of Financial Stress Indexes (FSIs)

Table A3: Granger Causality Tests – US Baa-Aaa (BBB-AAA) Corporate Spread, 1970-2016

1970-2016	3m	6m	12m	18m
D-star	0.1414	*0.0343*	0.1362	*0.0088*
	0.8933	0.9817	0.4136	0.5063
Slope	*0.0005*	*0.0015*	*0.0000*	*0.0000*
	0.0004	*0.0013*	*0.0022*	*0.0015*
Curvature	*0.0040*	*0.0118*	*0.0000*	*0.0000*
	0.0694	*0.0077*	*0.0042*	*0.0064*
1990-2016				
D-star	0.3363	0.2291	0.1735	*0.0431*
	0.5152	0.7172	0.7941	0.3593
Slope	0.7140	0.1959	0.1870	0.2138
	0.0208	*0.0173*	0.0541	0.0536
Curvature	0.5999	0.0843	0.1870	0.2138
	0.2634	0.1959	0.0541	0.0536

P-values shown. 3m, 6m, etc denotes the lead-time used to test Granger causality. Italics indicate significance at 5% level. D-star is the position of peak curvature. Slope is the 10 year-1 year Treasury yield spread. Curvature is the 1-5-10 year Treasury butterfly spread. The first row for each variable measures Granger causality 'from' the factor 'to' the target, and the second row shows the reverse causality 'from' the target 'to' the factor. Comment: The data from these bi-variant tests show evidence of one-way Granger causality of D-star on the Baa-Aaa (BBB-AAA) corporate spread around 18 months ahead over both the 1970-2016 period and the shorter 1990-2016 period. There is evidence of two-way causality for the yield curve and curvature factors over the full-sample, but less evidence of any causality in the recent 1990-2016 period.

Table A4: Granger Causality Tests – US B-Baa High Yield Corporate Spread, 1990-2016

1990-2016				
D-star	*0.0252*	*0.0027*	*0.0001*	*0.0000*
	0.7097	0.7377	0.7216	0.8631
Slope	0.0627	0.1777	0.1573	0.0527
	0.0000	*0.0002*	*0.0081*	*0.0158*
Curvature	*0.0005*	*0.0015*	*0.0284*	*0.0484*
	0.0000	*0.0000*	*0.0005*	*0.0002*

P-values shown. 3m, 6m, etc denotes the lead-time used to test Granger causality. Italics indicate significance at 5% level. D-star is the position of peak curvature. Slope is the 10 year-1 year Treasury yield spread. Curvature is the 1-5-10 year Treasury butterfly spread. The first row for each variable measures Granger causality 'from' the factor 'to' the target, and the second row shows the reverse causality 'from' the target 'to' the factor. Comment: The data from these bi-variant tests show evidence of one-way Granger causality of D-star on the high yield B-Baa/ BBB spread over all horizons during both sample periods. There is some evidence of two-way causality for the yield curve and curvature factors and even evidence of one-way reverse causality from the high yield spread on to the yield curve (1990-2016).

Table A5: Granger Causality Tests – US CCC-B Junk Spread, 1990-2016

1990-2016	3m	6m	12m	18m
D-star	*0.0247*	0.0580	*0.0030*	*0.0000*
	0.6653	0.5638	0.8870	0.7453
Slope	0.7227	0.6684	0.0810	0.1794
	0.0121	0.2457	0.1790	0.1366
Curvature	0.2634	0.7438	0.1970	0.4612
	0.0779	0.2926	0.0610	*0.0409*

P-values shown. 3m, 6m, etc denotes the lead-time used to test Granger causality. Italics indicate significance at 5% level. D-star is the position of peak curvature. Slope is the 10 year-1 year Treasury yield spread. Curvature is the 1-5-10 year Treasury butterfly spread. Comment: The data from these bi-variant tests show evidence of one-way Granger causality of D-star on the junk yield CCC-B spread over all horizons. There is some evidence of one-way reverse causality from the junk spread on to the yield curve and curvature.

Table A6: Granger Causality Tests – MOVE Index, 1990-2016

1990-2016	3m	6m	12m	18m
D-star	0.7306	0.5153	0.1497	*0.0370*
	0.8679	0.4971	0.1219	0.0909
Slope	0.9547	0.6005	0.0802	0.1470
	0.0000	*0.0000*	*0.0014*	*0.0206*
Curvature	0.1195	0.3000	0.1786	0.3708
	0.0000	*0.0000*	*0.0000*	*0.0004*

P-values shown. 3m, 6m, etc denotes the lead-time used to test Granger causality. Italics indicate significance at 5% level. D-star is the position of peak curvature. Slope is the 10 year-1 year Treasury yield spread. Curvature is the 1-5-10 year Treasury butterfly spread. The first row for each variable measures Granger causality ‘from’ the factor ‘to’ the target, and the second row shows the reverse causality ‘from’ the target ‘to’ the factor. Comment: The data from these bi-variant tests show evidence of one-way Granger causality of D-star on the MOVE index at 18 months over the 1990-2016 period. There is evidence of reverse one-way causality for the MOVE index on to the slope and curvature factors.

Table A7: Granger Causality Tests – CBoE VIX Index, 1990-2016

1990-2016	3m	6m	12m	18m
D-star	0.3895	0.0911	*0.0353*	*0.0577*
	0.8696	0.7752	0.8114	0.5011
Slope	0.9504	0.7380	0.0789	0.1985
	0.0330	0.1335	*0.0433*	0.3329
Curvature	0.6504	0.6486	*0.0089*	*0.0014*
	0.3049	0.2280	0.0551	0.2301

P-values shown. 3m, 6m, etc denotes the lead-time used to test Granger causality. Italics indicate significance at 5% level. D-star is the position of peak curvature. Slope is the 10 year-1 year Treasury yield spread. Curvature is the 1-5-10 year Treasury butterfly spread. The first row for each variable measures Granger causality ‘from’ the factor ‘to’ the target, and the second row shows the reverse causality ‘from’ the target ‘to’ the factor. Comment: The data from these bi-variant tests show evidence of one-way Granger causality of D-star and curvature on to the VIX index at 12 and 18 month horizons over the 1990-2016 period. There is evidence of reverse one-way causality for the VIX index on to the slope factor

(c) Measures of Business Activity

Table A8: Granger Causality Tests – US ISM Index, 1970-2016

1970-2016	3m	6m	12m	18m
D-star	0.1021	*0.0308*	*0.0221*	*0.0240*
	0.5376	0.6866	0.4843	0.5549
Slope	*0.0000*	*0.0003*	*0.0151*	*0.0003*
	0.0000	*0.0000*	*0.0000*	*0.0000*
Curvature	*0.0003*	*0.0012*	0.0705	*0.0045*
	0.0000	*0.0000*	*0.0000*	*0.0017*
1990-2016				
D-star	*0.0252*	*0.0027*	*0.0001*	*0.0000*
	0.7097	0.7377	0.7216	0.8631
Slope	0.0627	0.1777	0.1573	0.0527
	0.0000	*0.0002*	*0.0081*	*0.0158*
Curvature	*0.0005*	*0.0015*	*0.0284*	*0.0484*
	0.0000	*0.0000*	*0.0005*	*0.0002*

P-values shown. 3m, 6m, etc denotes the lead-time used to test Granger causality. Italics indicate significance at 5% level. D-star is the position of peak curvature. Slope is the 10 year-1 year Treasury yield spread. Curvature is the 1-5-10 year Treasury butterfly spread. The first row for each variable measures Granger causality 'from' the factor 'to' the target, and the second row shows the reverse causality 'from' the target 'to' the factor. Comment: The data from these bi-variant tests show evidence of one-way Granger causality of D-star on the ISM index between 6-18 months over the 1970-2016 period and one-way Granger causality over all spans during the shorter 1990-2016 period. There is evidence of two-way causality for the slope and curvature factors.

Table A9: Granger Causality Tests – Philadelphia Fed Manufacturing Index, 1970-2016

1970-2016	3m	6m	12m	18m
D-star	*0.0241*	*0.0387*	*0.0420*	*0.0357*
	0.3286	0.3603	0.3809	0.2299
Slope	0.1265	0.3171	0.4632	0.5319
	0.0000	*0.0001*	*0.0070*	*0.0404*
Curvature	*0.0003*	*0.0137*	*0.0266*	*0.0185*
	0.0017	*0.0266*	0.1283	0.2205
1990-2016				
D-star	*0.0381*	0.0867	*0.0417*	0.1093
	0.1687	0.0564	0.4102	0.4384
Slope	*0.0000*	*0.0000*	*0.0017*	*0.0021*
	0.0233	*0.0371*	0.0798	0.1029
Curvature	*0.0000*	*0.0000*	*0.0062*	*0.0015*
	0.0399	*0.0429*	0.1636	0.1029

P-values shown. 3m, 6m, etc denotes the lead-time used to test Granger causality. Italics indicate significance at 5% level. D-star is the position of peak curvature. Slope is the 10 year-1 year Treasury yield spread. Curvature is the 1-5-10 year Treasury butterfly spread. The first row for each variable measures Granger causality 'from' the factor 'to' the target, and the second row shows the reverse causality 'from' the target 'to' the factor. Comment: The data from these bi-variant tests show evidence of one-way Granger causality of D-star on the Philadelphia Fed index for all horizons over the 1970-2016 period and over 3 and 12 month spans during the shorter 1990-2016 period. There is evidence of two-way causality for the slope and curvature factors, but curvature performs better at 12-18 months. In the 1970-2016 period, slope shows reverse Granger causality.

Table A10: Granger Causality Tests – University of Michigan Consumer Sentiment Survey (12 month change), 1978-2016

1978-2016	3m	6m	12m	18m
D-star	0.1574	*0.0444*	0.2932	0.6482
	0.5500	0.4555	0.5850	0.6778
Slope	0.0825	0.2018	0.0551	0.2032
	0.1088	*0.0493*	0.2552	0.5621
Curvature	*0.0127*	0.0894	0.2254	0.8356
	0.6829	0.3183	0.7673	0.9210
1990-2016				
D-star	*0.0165*	*0.0006*	*0.0052*	0.0644
	0.6974	0.4744	0.7485	0.6431
Slope	0.1579	0.1389	0.1023	0.2226
	0.0041	0.1737	0.5936	0.7594
Curvature	0.2096	0.4339	0.8677	0.7865
	0.0457	*0.0483*	0.2916	0.5632

P-values shown. 3m, 6m, etc denotes the lead-time used to test Granger causality. Italics indicate significance at 5% level. D-star is the position of peak curvature. Slope is the 10 year-1 year Treasury yield spread. Curvature is the 1-5-10 year Treasury butterfly spread. The first row for each variable measures Granger causality 'from' the factor 'to' the target, and the second row shows the reverse causality 'from' the target 'to' the factor. Comment: The data from these bi-variant tests show evidence of one-way Granger causality of D-star on the change in consumer sentiment at 6 months over the 1970-2016 period and one-way Granger causality over 3-12 month spans during the shorter 1990-2016 period. There is evidence of one-way causality for the curvature factor at 3 months in the longer sample.

(d) Investors' Risk Appetite

Table A11: Granger Causality Tests – Variance-Based Risk Aversion, 1990-2016

1990-2016	3m	6m	12m	18m
D-star	0.5304	0.5027	0.1588	*0.0223*
	0.3182	0.1547	0.2133	0.3037
Slope	0.8145	0.6763	0.1222	*0.0223*
	0.0868	0.0902	0.2434	0.4226
Curvature	0.5105	0.7588	0.1390	0.0902
	0.4083	0.1217	0.6002	0.6437

P-values shown. 3m, 6m, etc denotes the lead-time used to test Granger causality. Italics indicate significance at 5% level. D-star is the position of peak curvature. Slope is the 10 year-1 year Treasury yield spread. Curvature is the 1-5-10 year Treasury butterfly spread. The first row for each variable measures Granger causality 'from' the factor 'to' the target, and the second row shows the reverse causality 'from' the target 'to' the factor. Comment: The data from these bi-variant tests show little evidence of one-way or two-way Granger causality for any on the factors on the variance measure of risk aversion over the 1990-2016 period. At the 18 month horizon the D-star and slope factors show some evidence of one-way causality.

Table A12: Granger Causality Tests – ECB World Risk Aversion Measure, 1998-2016

1998-2016	3m	6m	12m	18m
D-star	0.2478	*0.0234*	*0.0336*	*0.0048*
	0.4780	0.2137	*0.0145*	*0.0356*
Slope	0.8673	0.4270	0.0910	0.2453
	0.0166	0.0969	*0.0228*	0.0858
Curvature	0.9550	0.0958	*0.0307*	*0.0236*
	0.0765	0.1309	0.0897	0.0992

3m, 6m, etc denotes the lead-time used to test Granger causality. Italics indicate significance at 5% level. D-star is the position of peak curvature. Slope is the 10 year-1 year Treasury yield spread. Curvature is the 1-5-10 year Treasury butterfly spread. The first row for each variable measures Granger causality 'from' the factor 'to' the target, and the second row shows the reverse causality 'from' the target 'to' the factor. Comment: The data from these bi-variant tests show evidence of one-way Granger causality of D-star on the ECB Risk Appetite measure at 6 months over the 1998-2016 period and two-way causality at longer horizons. There is evidence of reverse one-way causality for the US FCI on to the slope factor. Curvature shows one-way causality at 12-18 months.

Table A13: Granger Causality Tests – CrossBorder Capital Risk Appetite Index (12 month change), 1978-2016

1978-2016	3m	6m	12m	18m
D-star	0.2698	0.1797	0.1186	*0.0173*
	0.0946	*0.0265*	*0.0011*	*0.0009*
Slope	0.5501	0.3977	0.0440	0.2069
	0.0208	*0.0258*	0.4066	0.2502
Curvature	*0.7750*	*0.0261*	0.0568	0.2271
	0.0114	*0.0083*	0.0876	0.1112
1990-2016				
D-star	*0.0145*	*0.0115*	*0.0333*	*0.0452*
	0.0032	*0.0022*	*0.0031*	*0.0181*
Slope	0.4528	0.2096	0.1254	*0.0380*
	0.0218	0.0748	0.1233	0.3048
Curvature	0.8322	*0.0095*	0.2759	*0.0468*
	0.0002	*0.0018*	*0.0039*	*0.0371*

3m, 6m, etc denotes the lead-time used to test Granger causality. Italics indicate significance at 5% level. D-star is the position of peak curvature. Slope is the 10 year-1 year Treasury yield spread. Curvature is the 1-5-10 year Treasury butterfly spread. The first row for each variable measures Granger causality 'from' the factor 'to' the target, and the second row shows the reverse causality 'from' the target 'to' the factor. Comment: The data from these bi-variant tests show evidence of two-way Granger causality of D-star on the CBC Risk Appetite measure over all horizons in the 1990-2016 sample and at 18 months in the longer sample. There is evidence of reverse one-way causality for the CBC index on to the slope factor and curvature factors at several horizons, but the slope shows one-way causality at 18 months in the shorter sample.

Chapter 5

Do Central Bank Asset Purchases Drive Treasury Yields Higher or Lower? – An Investigation of the Risk-Taking Policy Transmission Channel

5.1 Large-Scale Asset Purchases and Risk Premia

Financial shocks often alter the way that investors and credit providers assess risk. When this affects their willingness to take on risk exposures, it can lead to abrupt changes in both term and general risk premia. These effects are collectively called the *risk-taking* policy transmission channel (see Adrian and Shin, 2010; Borio and Zhu, 2012, and Bruno and Shin, 2014). In this chapter, I explore this *risk-taking channel* from the recent experience of large-scale asset purchases, or LSAP[45] (popularly known as QE1, QE2 and QE3), and, using a vector auto-regression model (VAR), I seek to better understand what factors drive Treasury term premia and corporate credit risk premia, and so govern their subsequent interaction. I introduce a new measure of *risk appetite* and integrate broad liquidity measures into asset pricing, taking into account the effects of shadow banks and foreign investors. I argue that many recent LSAP studies (see Krishnamurthy and Vissing-Jorgensen, 2011 and Gagnon, 2016, for a summary) have flaws: for example, they ignore the substitution and dynamic effects that cause changes in the overall demand for *safe assets*, such as Treasury securities. Consequently, these event studies often reach perverse conclusions about asset prices and rarely acknowledge that the effectiveness of LSAP is typically conditional on the state of the economy, since consistent policy transmission crucially depends of the persistence of extant informational and market frictions. This implies that the efficacy of different LSAP will vary and it may explain why Martin and Milas (2012) find that the effects of QE1 on markets are larger than those of QE2.

[45] Unconventional monetary policies are understood to largely comprise: (1) ‘forward guidance’ – the communication by the US FOMC about the likely future path of the Federal Funds rate over the next several quarters, and (2) ‘large scale asset purchases’ (LSAP), also known as QE (quantitative easing) – purchases by the Federal Reserve of hundreds of billions of dollars worth of longer-term assets, such as US Treasuries and mortgage-backed securities (MBS). They also include the ‘floor system’ on interest rates paid on reserves and the Troubled Asset Relief Programme (TARP). Conventional monetary policies relate to interest rate setting to achieve inflation (and, in cases, unemployment) targets.

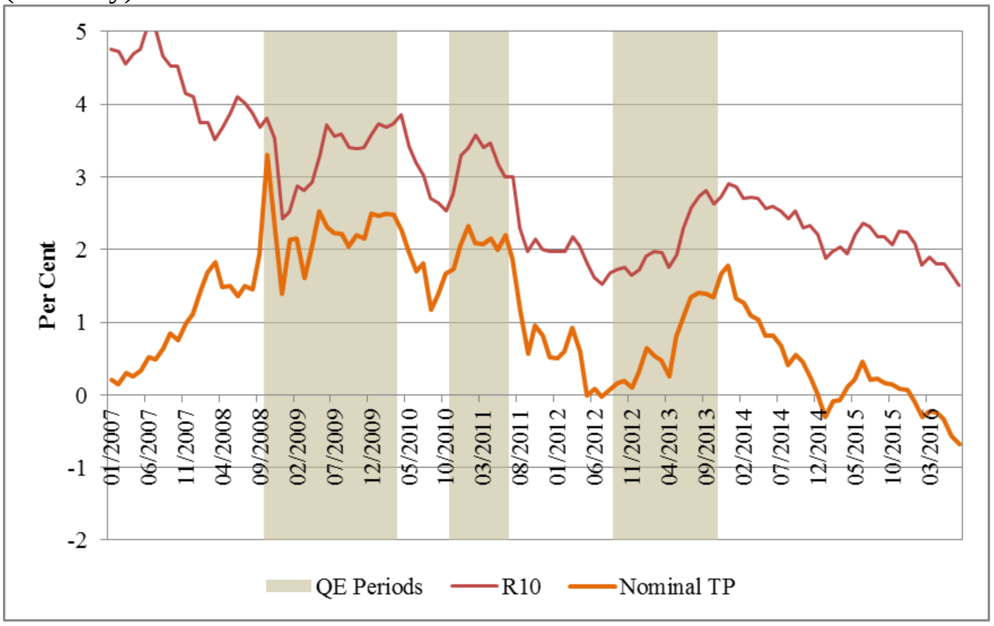
Hanson, Lucca and Wright (2017) pose this problem in a different way. They note that the positive correlation between short-term and long-term bond yields that was evident across both high and low-frequency samples prior to year 2000, has since fallen noticeably at low frequencies, overlapping the period of LSAP. According to the expectations hypothesis, there should anyway only be a limited relationship between short-term and long-term yields, unless policy interest rate shocks are considered to be persistent. Yet, the existence of institutional frictions provides plausible reasons for this positive relationship. These have been collectively termed *amplification mechanisms* by Shin (2017). They include the 'reach for yield', where certain agents with a preference for high coupon yields are forced to move further out along the yield curve, substituting high for low maturity bonds. Similarly, there are 'hunt for duration' (Domanski et al., 2015) and 'mortgage convexity' effects, following pre-payments and loan re-financings. These lead to negative convexity in the term structure, when expectations of falling yields cause a greater demand for scarce duration, which, in turn, drive yields still lower. In addition, Cieslak and Povala (2014) observe that some investors trend-follow, while low (high) interest rates may themselves also induce a persistence in risk-seeking (risk-avoiding) behaviour.

A puzzle is why this term premia effect should weaken over time and even reverse over longer horizons? Hanson, Lucca and Wright (2017) use a model with slow-moving capital to explain how the demand curve for maturity becomes progressively more elastic with respect to yields. My argument is different. LSAP policies effectively force the private sector to substitute cash for bonds. The reduction in the supply of bonds to the private sector decreases the amount of outstanding duration risk[46] and, given preferred habitats, also creates scarcity effects that together lower term premia. However, the impact of the announcement of policy action, combined with the injection of more liquidity into markets, reduces perceived systemic risks, increases investors' confidence and so encourages the private sector to cut its demand for safe assets, including Treasury bonds. This causes the demand curve for maturity to shift leftwards and so drive up term premia as investors become more risk-seeking. Indeed, Bhattarai and Neely (2016) acknowledge that "…*LSAPs can also lead to lower investor risk*

[46] Duration is defined in Chapter 2.

aversion by generating expectations of improved financial and macroeconomic conditions."

Figure 22: US QE Periods, Nominal Term Premia and 10-Year Treasury Yield, 2007-16 (Monthly)



Source: FRBNY, FRB

The chart shows the relationship between the US Treasury 10-year yield and the implied nominal term premia. Apart from 2007-mid-2008, the two series closely correlate and move together through the announced QE-periods, i.e. QE1, QE2 and QE3. Contrary to expectations, both series tend to rise through the QE-on period and fall in the QE-off periods, some 67% of the time. This appears inconsistent with event studies, but aligns with a credit/ risk-taking transmission process where more Fed liquidity lowers systemic risks.

Put differently, the demand curve for maturity is conditional on the actions of policy-makers, because US Treasury securities, which are a main instrument of these LSAP, serve as safe assets for many investor types. Treasuries are primarily demanded for safety reasons, because of their attributes of liquidity, low default risk, use as collateral, immunization and stable value. Like other assets, a decrease in the supply of Treasuries to the private sector will lead to upward pressure on their prices, assuming that the demand curve remains largely unaffected. Yet, the very act of purchasing Treasuries by the Federal Reserve results in a simultaneous increase in the supply of cash, another safe asset. This leads to an increase in the demand for Treasury substitutes (such as high quality, similar duration mortgage and corporate bonds), but it may also cause a parallel drop in the demand for Treasuries and other safe assets and increase investors' appetite for riskier securities, to the extent that this direct supply of cash and the indirect confidence effect from official actions succeed in reducing systemic risks. Thus, contrary to the standard narrative, Treasury term premia and yields could rise and correlate negatively with widespread falls in the risk premia and yields associated with more risky assets, such as corporate credits.

While the existing finance literature provides plausible estimates of the size of US Treasury term premia (Gurkaynak, Sack, and Wright, 2006, and Adrian et al. 2014) and corporate credit spreads (Gilchrist and Zakrajsek, 2012), it is less able to explain the factors that drive them and so accurately forecast their future movements (Duffee, 2012). In line with these concerns, term premia have lately moved in the opposite direction to that predicted by the experts by rising following LSAP rather than falling. A time-series plot of monthly US data covering the recent LSAP episodes in Figure 22 shows that these quantitative easing policies appear to be consistent with rising, rather than falling US Treasury term premia and 10-year Treasury yields. In the six years following the 2007/08 Global Financial Crisis (GFC), US 10-year Treasury yields generally rose with term premia during 'QE-On' periods and fell with term premia during 'QE-Off' periods (correlation coefficient 0.257 to the binary event of a QE period and with common co-movements in 67% of months)[47]. This observation stands in direct opposition to the accepted view, articulated in many recent event studies (Gagnon, 2016), that the LSAP policy response (as detailed in Appendix 5A) to the GFC should lead to lower bond term premia.

The chapter is organized as follows: the next section describes the empirical results from recent event studies. Section 5.3 reviews the transmission channel literature. Section 5.4 discusses the proposed VAR model. Section 5.5 describes the data and Bayesian VAR estimation. The resulting impact of liquidity and risk appetite on risk premia is summarised in Section 5.6. Section 5.7 concludes.

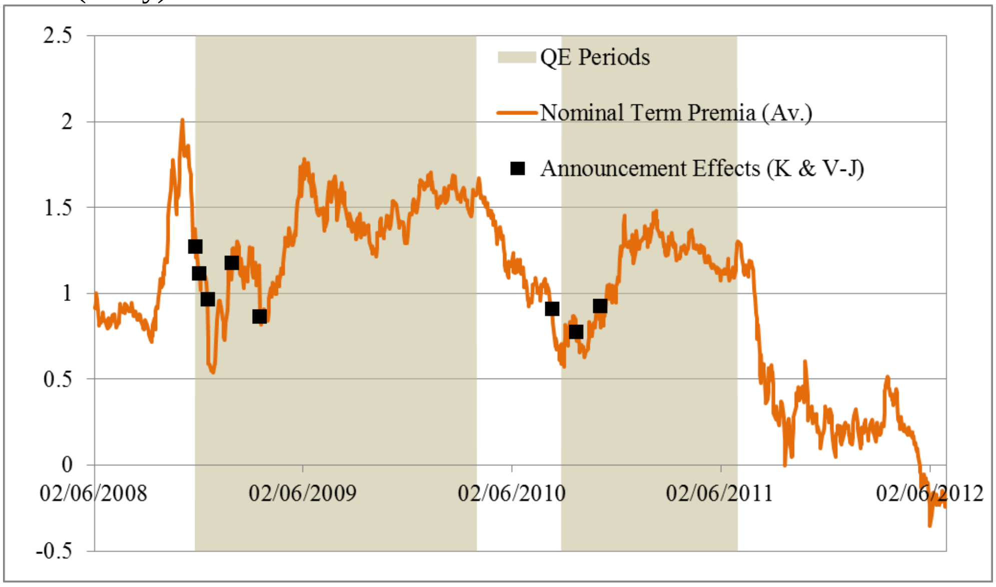
[47] The correlation between nominal term premia and 10-year yields jumped to 0.918 over the same period. In other words, changes in interest rate expectations apparently played little role.

5.2 Event Studies

In their widely-quoted event study, Krishnamurthy and Vissing-Jorgensen (2011) examine the impact of unconventional monetary policies on US Treasuries and mortgage-backed securities (MBS), concluding that the announcement effect of planned Federal Reserve buying raises government bond prices (decreases yields)[48]. Their event study covers QE1 (December 2008 – March 2010) and QE2 (November 2010 – June 2011). It explores several transmission channels and extends the original insights made about portfolio balance effects by Tobin (1958 and 1969) to include the supplies of other securities, while acknowledging that US Treasuries have risk-free, or safety, attributes[49]. They assign most of the change in term premia to a, so-called, safety channel. Their approach fits in with the *preferred habitat* model (Modigliani and Sutch, 1966; Vayanos and Vila, 2009), as applied to liability immunization (Bierwag and Kaufman, 1985, and Domanski, Shin and Sushko, 2015), and with the safe asset shortage argument of Caballero (2006). Their focus on a narrow window of 2-day price movements may explain why some of their conclusions appear to be reversed over the medium-term. Event studies have been criticised as myopic because they use high frequency data and do not look far enough ahead to capture the full dynamic impact of LSAP in reducing general credit risk, but they also fail to bring in effects from other domestic and foreign liquidity providers (Adrian, Moench and Shin, 2010; Rey, 2016 and Hanson, Lucca and Wright, 2017). Krishnamurthy and Vissing-Jorgensen are not alone in making their claims as Table 9 shows. For example, a recent study by Swanson (2015), using principal components to identify and quantify the *forward guidance* and LSAP dimensions of Federal Reserve policy, similarly appears to show that FOMC announcements immediately push down both Treasury and corporate yields. (See also D'Amico, 2012; Neely, 2015; Gagnon et al. 2011, and Joyce et al. 2010). The former FOMC member Jeremy Stein (2012) is unequivocal: *"…*[it] *seems clear from the data that if you buy a lot of long-term Treasury securities, this exerts significant downward pressure on their yields and term premiums …*"

[48] *"…it is clear from this body of evidence that QE lowers medium- and long-term interest rates…"(p216).*
[49] Krishnamurthy and Vissing-Jorgensen (2010) argue that Treasuries are 'money-like' and when their supply as % of GDP is low, the value assigned to their liquidity and safety attributes is relatively high (Aaa-Treasury spread).

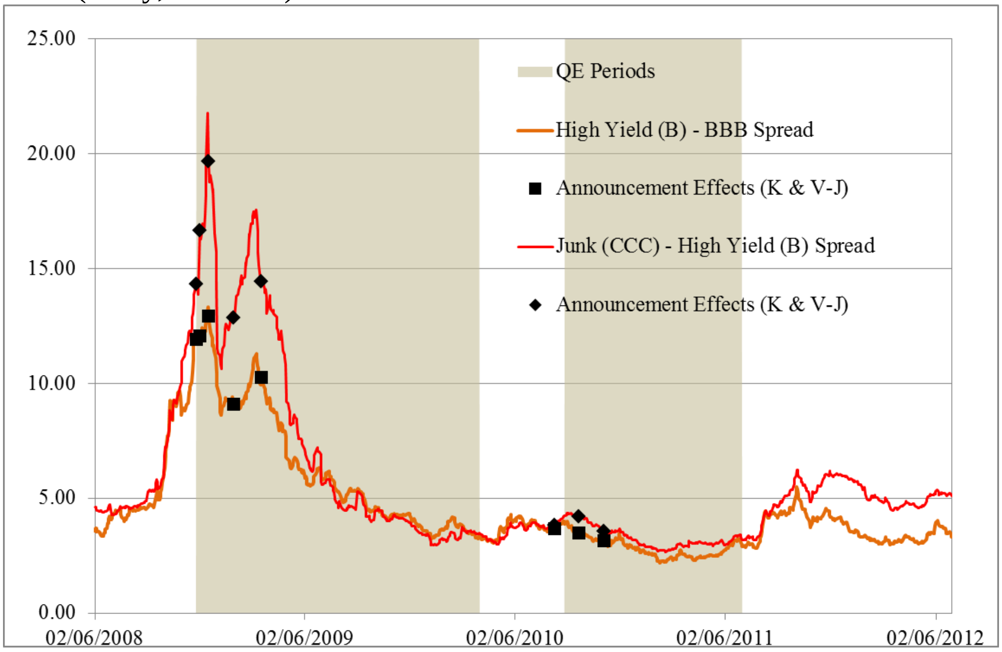
Figure 23: US Treasury Nominal Term Premia and LSAP Announcement Effects, 2008-2012 (Daily)



Source: FRBNY, Krishnamurthy and Vissing-Jorgensen (2011)

Comment: In five out of eight event studies Treasury term premia fell immediately following LSAP. However, in all eight cases these term premia subsequently rose in the following 3-6 months.

Figure 24: US Corporate Credit Risk Premia (Junk CCC less High Yield Single B and High Yield (B) less Investment Grade (BBB)) and LSAP Announcement Effects, 2008-2012 (Daily, Per Cent)



Source: FRBNY, FRED, Krishnamurthy and Vissing-Jorgensen (2011)

Comment: In general, the two credit risk premia – the junk spread and the high yield spread – move together. In two cases highlighted, the corporate credit spread immediately widened within 1-2 days of the announcement effects; in three cases they fell and in three other cases the evidence is mixed. However, looking 3-6 months further ahead, corporate spreads narrowed significantly, notably following QE1.

Table 9: Estimated Effects of Quantitative Easing (LSAP) on 10-year Bond Yields

Study	Sample	Method	Yield reduction (bps)
United States			
Greenwood and Vayanos (2008)[a]	1952-2005	Time series	82
Gagnon, Raskin, Remache & Sack (2011)	2008-09	Event study	78
Gagnon, Raskin, Remache & Sack (2011)	1985-2007	Time series TP only	44
Krishnamurthy & Vissing-Jorgensen (2011)	2008-09	Event study	91
Krishnamurthy & Vissing-Jorgensen (2011)	2010-11	Event study	47
Hamilton & Wu (2012)	1990-2007	Affine model	47
Swanson (2011)	1961	Event study	88
D'Amico & King (2013)	2009-10	Micro event study	240
D'Amico, English, Lopez-Salido & Nelson (2012)	2002-08	Weekly time series	165
Li & Wei (2012)	1994-2007	Affine model of TP	57
Rosa (2012)	2008-10	Event study	42
Neely (2012)	2008-09	Event study	84
Bauer & Neely (2012)	2008-09	Event study	80
Bauer & Rudebusch (2011)b	2008-09	Event study TP only	44
Christensen & Rudebusch (2012)[b]	2008-09	Event study TP only	26
Chadha, Turner & Zampolli (2013)	1990-2008	Time series TP only	56
Swanson (2015)[b]	2009-15	Yield curve TP only	40
Christensen & Rudebusch (201d)[b]	2008-09	Event study TP only	15
United Kingdom			
Joyce, Lasaosa, Stevens & Tong (2011)	2009	Event study	78
Joyce, Lasaosa, Stevens & Tong (2011)	1991-2007	Time series	51
Christensen & Rudebusch (2012)[b]	2009-11	Event study TP only	34
Churm, Joyce, Kapetanios & Theodoris (2015)	2011-12	Intl. comparison	42
Japan			
Fukunaga, Kato & Koeda (2015)	1992-2014	Time series TP only	24
Fukunaga, Kato & Koeda (2015)	2013-14	Event study	17
Eurozone			
Middeldorp (2015)[c]	2013-15	Event study	45-132
Altavilla, Carboni & Motto (2015)[d]	2014-15	Event study	44
Middeldorp & Wood (2016)[c]	2015	Event study	41-104
Sweden			
De Rezende, Kjellberg & Tysklind (2015)	2015	Event study	68

Notes: [a] Greenwood & Vayanos scaled the effect relative to the size of the Treasury market. The estimate here is based on the ratio of Treasury debt to GDP in 2015. [b] These studies further differentiate between signaling effects and portfolio effects. The reported estimate is for the portfolio effect only. [c] The smaller estimate is for German bonds and the larger one is for Italian bonds. [d] The estimate is for an average of Eurozone bonds.

Purchases normalised to 10% of GDP. 100bp equals one % point. Most studies present a range of estimates. The Table displays the preferred estimate if one exists. If not, it presents the midpoint of the range. For event studies, the purchases are normalised by all long-term bonds, not just government bonds. Some of the non-event studies include non-government bond purchases and others do not. "TP only" denotes studies that attempt to estimate the term premium component of movements in bond yields. For event studies, the normalisation is based on GDP in the final year of the event.

Source: Gagnon (2016)

Figures 23 and 24 put the Krishnamurthy and Vissing-Jorgensen event studies into a longer-term context by extending the daily data span several months ahead and analysing the estimated term premia component of US Treasury yields and the CCC less single B-rated corporate credit risk spread. Admittedly, Krishnamurthy and Vissing-Jorgensen focus on nominal bond yields, whereas the data reported in Figures 22 and 23 refer to the underlying Treasury term premia component. However, this latter channel is how many investors understand the transmission process, since LSAP are thought to affect interest rate expectations through a *signalling channel*, and term premia via portfolio effects (Engen, 2015 and Bhattarai and Neely, 2016). The data are derived from a decomposition of nominal Treasury yields into: (1) real interest rates; (2) inflation expectations and (3) term premia. See equation (6) below. Term premia cover dimensions such as *default risk, duration risk, prepayment risk, inflation risk, liquidity, safety* and *local scarcity*. By definition, they are the excess yields that investors require to commit to holding long-term government bonds instead of a series of shorter-term bonds. For example, suppose that the interest rate on the 10-year U.S. Treasury note is 2.5%, and assume that the interest rate on the 1-year U.S. Treasury bill is expected to average 2% over the next 10 years. Then the nominal *term premium* on the 10-year U.S. Treasury note would be 0.5% (50 basis points)[50]. The contribution to yields of each component varies both over time and with the holding period. Kim and Orphanides (2007) argue that the behaviour of long-term Treasury yields cannot be explained by changes to interest rate expectations alone. Calculations by Adrian et al. (2014) agree. Their data shows that whereas short-dated US Treasury yields are largely determined by nominal interest rate expectations, movements in term premia dominate the yields of long-dated bonds. We know from Cieslak and Povala (2014) that term premia effects are cyclical, i.e. mean-reverting, and they ultimately wash-out of yields because real interest rates determine the slope of the yield curve over very long-term spans:

$$y_t^m = \frac{1}{m}\sum_{i=0}^{m-1} E_t R_{t+i} + \frac{1}{m}\sum_{i=1}^{m} E_t \pi_{t+i} + tp_t^m \qquad (6)$$

[50] Term premia are usually positive, but they can be negative

where y_t^m is the spot yield of a bond of maturity m at time t; E_t denotes the expectations operator; R_t is the real interest rate; π_t is the inflation rate; tp_t^m represents the nominal term premium over a holding period m

I use the daily cross-sectional average US Treasury term premia data provided by Adrian et al. (2014). These are unobservable variables and estimated with errors (see Rudebusch et al, 2007), but these estimates appear plausible and they are officially published by the Federal Reserve Bank of New York. I assume that monetary policy does not affect the parametric structure of the model that generates these estimates. For the credit risk premia, I take the spread between triple CCC-rated (or 'Junk' debt) and single B-rated ('high yield') US corporate bonds, as published by Bank of America/ Merrill Lynch and downloaded from the FRED database. This spread measures the incremental risk premia required to hold the securities of US corporations in or close to bankruptcy. Similar results come from using the B-BBB[51] spread versus investment grade. These securities should be especially sensitive to changes in systemic financial conditions and it has been found that their risk spreads play an important role in the broad transmission of monetary policy via the balance sheets of financial intermediaries (Adrian, Moench and Shin, 2010). The daily risk premia data appear to confirm the message from Figure 22 that LSAP have been more often associated with rising, not falling, US Treasury term premia and with collapsing credit risk premia over a timespan of several months. The average term premium across 1-to-10 year US Treasuries in QE1 (QE2) averaged 132bp (109bp) in the 60 days prior to the announcement effects sampled by Krishnamurthy and Vissing-Jorgensen and a slightly higher 135bp (110bp) through the remainder of the two respective QE periods. During their event studies, Treasury term premia fell following the LSAP announcement in five out of eight cases, but rose in all eight cases over subsequent months. Perversely, corporate credit spreads immediately widened in two cases following the announcement effects and only unambiguously fell in three cases. However, within 3-6 months, these credit risk spreads narrowed significantly, notably in the wake of QE1.

These positive impacts on Treasury term premia motivate me to ask whether the various event studies have sufficiently questioned the data? The LSAP literature's focus on

[51] S&P categorize an 'investment grade' bond as *BBB* and above: Moody's use the alternative *Baa* label

supply and its implicit assumption that the private sector's demand for Treasuries is unaffected misses more important fluctuations in both the bank and non-bank private sector's demand for safety that may follow policy changes. These endogenous links between liquidity, induced changes in risk appetite and the pricing of risk has been termed the *risk-taking channel*. It includes the positive effect following improvements in borrower collateral, which can foster additional risk-taking by banks (Bernanke and Gertler, 1989), and it is consistent with the positive feedbacks that occur between so-called *funding liquidity* and *market liquidity* (Brunnermeier and Pedersen, 2009). This channel has been largely absent from traditional narratives, but it may help to explain the anomalous movements of Treasury yields in these event studies.

5.3 Review of Transmission Channel Literature

The policy *risk-taking channel* represents a hybrid between the standard Keynesian transmission mechanism of portfolio balance (Tobin, 1969); the more recent focus on funding sources (Brunnermeier, 2009, and Gorton, 2012); an international dimension (Rey, 2016) and the concept of safe assets (Caballero, 2006). A safe asset is a financial instrument that provides: (1) low market and credit risks; (2) high market liquidity; (3) limited inflation risks; (4) low exchange rate risks and (5) limited idiosyncratic risks (IMF, 2012). It will likely correlate negatively with investors' risk appetite. The canonical safe asset is the 10-year Treasury note, but the list includes all assets that are used in an information-insensitive fashion (Gorton et al, 2012). The supply of these assets is not perfectly elastic and may have an associated cost similar to the 'Triffin Dilemna' (Portes, 2013). Supply shortages can occur because of regulation, Central Bank LSAP, credit rating agency downgrades and falls in investors' risk appetite. It is suggested in the literature that shortages in the supply of safe assets lead to macroeconomic disequilibria and greater financial stress (Caballero, 2006). Krishnamurthy and Vissing-Jorgensen (2013) claim that the increasing supplies of US Treasuries reduce the probability of crises. Many policy-makers are alert to the threat to the global financial system of a structural shortage of these safe assets (IMF, 2012).

Much of the early economics and finance literature ignores funding issues and institutional structure, possibly under the influence of Modigliani and Miller (1958) and

Friedman (1968). It focusses, instead, on the effect of the Federal Reserve, as an interest rate-setter and a reserve-provider, acting on a narrow monetary aggregate, such as M2 that largely consists of the government-insured retail deposit liabilities of domestic high street banks. In a Modigliani and Miller World, economic agents are never finance or liquidity-constrained, and there are no feedbacks from the liability structure back on to the asset structure, as might, for example, occur when collateral effects affect the transmission mechanism by boosting borrowing potential or concerns over net worth and capital adequacy limit future funding opportunities. Wallace (1981) has shown that under these assumptions, changes in the size and composition of the monetary authorities' balance sheet are neutral. As a result, specific financial frictions have to be introduced into models, such as the heterogeneity of investors' asset preferences; various market segmentations, and limits to arbitrage sufficient for assets to be imperfect substitutes. With imperfect substitutability, LSAP alter the relative supplies of assets and change term and risk premia through a portfolio balance channel. This literature can be categorised into four distinct parts: (1) the transmission of Treasury supply factors (LSAP) on to asset prices; (2) the effect of asset prices and maturity composition on financial stability; (3) the importance of Treasury supply for financial intermediation in the credit and repo markets and its implications for the shape of the term structure, and (4) the transmission of monetary shocks to the real economy through term premia and the term structure.

The impact of policy change is traditionally framed in terms of monetary shocks, rather than these Treasury supply shocks. The conventional monetary transmission mechanism comprises several possible channels: (1) *credit and liquidity* (Bernanke and Blinder, 1992); (2) *bank capital and bank balance sheets* (Van den Heuvel, 2007); (3) *risk appetite* – arising from, say, changes in investors' perceptions of default risk, duration risk and systemic risk (Borio and Zhu, 2012); (4) *portfolio balance* – through factors such as duration and safety (Tobin, 1958, 1969), and (5) *borrower net worth and balance sheet strength*, which improve the quality of loan collateral (Bernanke and Gertler, 1989). Treasury supply changes, following, say, LSAP, are likely also transmitted through similar channels. The literature is less clear about precisely how this transmission operates, but it broadly takes three forms: (i) a *calming effect* during financial crises when Central Bank purchases act as 'buyer of the last resort'; (ii) a *signalling effect* that reinforces existing 'forward guidance' policies (see Appendix A), and (iii) a *portfolio channel*, where LSAP affect duration, credit and liquidity risk by creating a scarcity of Treasury securities (See D'Amico et al. 2012 and Vayanos and Vila, 2009). Krishnamurthy and Vissing-Jorgensen (2011) study a number of additional channels and conclude that *signalling*, *inflation* and *safety* channels worked in both QE1 and QE2; that *prepayment*, *default* and *liquidity* channels worked in QE1, but not QE2, and they found no evidence for a *duration* channel. They quantify the size of the *safety* channel at 160bp, based on residual effects, and argue that it applies consistently throughout QE1 and QE2. Gagnon (2016) summarises the recent empirical experience (see Table 9). Collectively, these studies require strong assumptions for identification and Wright (2011) warns about the consistency of the loadings. Their empirical results appear far from robust and their range is particularly wide, with estimates of the impact effect of LSAP on the nominal ten-year Treasury yield ranging from 15 basis points (bp) to more than 240bp, according to the data reported earlier in Table 9. Moreover, these data are, themselves, often averages that blend together the various LSAP episodes, without discriminating between the relative effectiveness of QE1, QE2 and QE3, and specifically the 'novelty' effect of QE1. There are also disturbing inconsistencies: simulations by Engen (2015) suggest that a LSAP programme sized to reduce 10-year Treasury yields by 20bp, only lower BBB investment grade corporate yields by 15bp, thereby perversely widening corporate credit spreads. Hamilton and Wu (2012) also find an inverse effect in QE2, where Treasury yields and term premia increased.

Goodhart and Perotti (2015) explain the recent incidence of financial crises by linking the maturity mismatch of banks to liquidity strains. They argue that these crises result from the growth of wholesale funding markets in short-term liabilities and in the parallel shift of banks' loan books towards longer-dated real estate assets (Jorda, Schularick and Taylor, 2015). These give rise to balance sheet illiquidity and in 2007/08 led to a large maturity mismatch between assets and liabilities. In general, private banks and other financial institutions perform both liquidity and maturity transformation functions (Diamond and Dybvig, 1983, and Williamson, 2012), but their liabilities differ by marketability and their assets have credit risk, so making them less safe than government securities. The literature recognizes these agency problems as an important source of business cycle amplification. (See Bernanke and Gertler, 1989 and Kiyotaki and Moore, 1997). Borio and Zhu (2012) and Bruno and Shin (2015) describe a policy *risk-taking channel* where financial intermediation plays a key role. These financial intermediaries are assumed to be risk-neutral, leveraged and subject to value-at-risk (VaR) constraints. Positive shocks raise their demands for assets and compress risk premia, which, in turn, by further relaxing internal VaR constraints, allow greater leverage. Looser monetary policy, by lowering financing costs, drives a positive feedback loop, thereby creating a pro-cyclicality of leverage that can threaten financial stability. (See D'Arista, 2009; Gourinchas and Obstfeld, 2012 and Schularick and Taylor, 2012).

In an earlier study of private financial intermediaries, Shin (2010) distinguishes between the gross size of financial balance sheets and the less important, but more traditional, net balance sheet size (i.e. net worth) which excludes inter-lender payment flows. He argues that long chains of financial intermediation highlight greater counterparty risk, since these imply a growing reliance on short-term and highly pro-cyclical financing. Shin also shows how the *liability immunisation* policies of these institutions can be destabilising, because when liabilities change faster than assets, the demand for duration-matching instruments can be excessive. He concludes that these structural changes explain the rapid growth in repos and the over-sized impact of short-term policy rates on the credit markets. The use of repos and, hence, leverage depend heavily on the shape of the yield curve. It has been known for some time that the yield curve can predict future macro-economic conditions (Estrella and Hardouvelis, 1991 and Moench, 2012), but it has only recently been introduced as a transmission variable in macro-economic models. (See Wu, 2001; Ang and Piazzesi, 2001; Evans and Marshall, 2007, and Ludvigson and Ng, 2009). Estrella and Hardouvelis show how a flattening yield curve precedes a slower economy by around one year, which should also lead to higher default risks being subsequently discounted into credit spreads. It follows that, as the yield curve flattens and Treasury term premia narrow, so there occurs a corresponding rise in risk premia attached to other more risky instruments.

To quantify these term premia, Adrian et al. (2013) develop statistical methods to decompose nominal US Treasury yields into expected short-term rates and term premia. They use a five-factor model, justified following a Wald test on the rank of the factor matrix, rather than the similar three-factor 'no arbitrage' model employed by Kim and Wright (2005). Theoretical macroeconomic models typically argue that term premia do not matter, but the authors show that their term premia estimates are elevated when both unemployment and measures of uncertainty are high. However, they find little evidence that term premia rise when monetary policy tightens. In a parallel study, Rudebusch, Sack and Swanson (2007) give support to the observation made by the former Federal Reserve Chairman (Bernanke, 2006) that declines in term premia are financially stimulative, rather than recessionary as many previous empirical studies show. They conclude that policymakers should still assess the source of the change in term premia, since only those monetary policy and supply shocks that narrow term premia are likely to be stimulative. Bauer and Hamilton (2015) question many of these statistical test results, concluding that only the yield curve level and slope are robust predictors of excess returns and there is no convincing evidence of unspanned macro risks. Gilchrist, Yankov and Zakrajsek (2009) find that unexpected shocks to credit spreads, especially of medium rather than low grade issuers, account for a large proportion of the variation in economic activity two-to-four years ahead. In a recent follow-up, Gilchrist and Zakrajsek (2012) show how changes in the credit-worthiness of broker-dealers cause shocks to excess bond premia, after removing an expected default component. These shocks lead to a fall in the financial sector's effective risk-taking capacity, reduced credit supply and less favourable economic conditions.

Although these *credit* and *risk-taking* channels have been mostly studied for closed economies, there is growing evidence that they might be also relevant in an international context, particularly given the significance of foreign activity in the US Treasury market. Net foreign buying of Treasuries has obvious parallels to the LSAP programme because the effective supply of safe assets is reduced as they are bid away from domestic holders. The literature largely focuses on 'global imbalances' (See Caballero, 2006; Caballero, Farhi and Gourinchas, 2008, and Caballero and Krishnamurthy, 2009). The transmission of US monetary policy shocks to the rest of the World is not well-understood, but it is known that global banks finance cross-border lending to regional borrowers by tapping US dollar money market funds in the key financial centres, notably the Eurodollar markets. These wholesale funding pools are traditionally fed by US dollar revenues from oil and commodity producers, but they have lately enjoyed a windfall from buoyant US corporate cash flows[52]. Their recent expansion questions the

[52] Under new liquidity coverage regulations, corporate deposits have become less attractive to domestic US banks.

ability of national economies to achieve monetary independence even under flexible exchange rates, so contradicting Mundell's policy trilemma (Rey, 2016). Miranda-Agrippino and Rey (2015) show that US monetary policy affects risk premia, international leverage and credit growth, which appears consistent with both the *credit channel* and the *risk-taking channels* of monetary policy. The empirical studies again disagree about the size of the impact effect from foreign buying on US Treasury yields. Warnock and Warnock (2009) estimate the impact effect of foreign official purchases of US Treasuries at around 80 basis points. Krishnamurthy and Vissing-Jorgensen (2012) find that falls in foreign holdings increase long-term Treasury yields by 59 basis points relative to the Baa (BBB) corporate bond yield. In contrast, Sierra (2010) finds little effect on US Treasury bond yields from foreign investors at the 10-year maturity.

5.4 Quantifying the Effects of Liquidity and Risk Appetite

The specific claims made about Treasury term premia by event studies run counter both to the longer-horizon time-series evidence and to the impulse response functions estimated from a Bayesian VAR model. I construct this VAR to better understand the role of term and credit risk premia in policy transmission, again taking US Treasury term premia estimates from Adrian et al. (2014) and corporate credit spreads, as measured by the Bank of America/ Merrill Lynch benchmark series. Changes in the excess demand for longer duration safe assets are modelled using a *risk appetite*[53] variable labelled D-star that represents the position of the peak curvature of the US Treasury term structure along the maturity axis. Underlying the D-star statistic is a preferred habitat framework that generates a derived demand for maturity based on duration needs. Leibowitz, Bova and Kogelman (2014) and Greenwood, Hanson and Stein (2010) collectively evidence that institutional investors and corporate financial managers target liability duration to guide their choice of safe assets. Intuitively, as the risk appetites of investors and credit providers improve, their investment horizons should lengthen and lending and liquidity conditions expand, so encouraging investors to move further out along the 'risk curve' and into longer duration, less liquid and more volatile instruments. In modern investment parlance, this describes a shift towards 'Risk

[53] *Risk appetite* as defined by Gai & Vause (2006) to distinguish it from both *risk aversion* and *riskiness*.

On'-type strategies (i.e. risk-seeking), such as equities and corporate debt, and away from ‘Risk Off’-type strategies, such as holding safe asset Treasury bonds and cash.

As these assets re-price, so their implied term and risk premia change. The increase in risk appetite reduces the demand for safe asset duration, so lifting local term premia. This *risk-taking policy transmission channel* pushes up the prices of risky assets and lowers the prices of safe assets. This is consistent with the interpretation that greater risk-seeking activity (i.e. a rise in D-star), possibly encouraged by an increase in LSAP and Federal Reserve liquidity injections, leads to the substitution of safe Treasuries for riskier corporate credits. It may also include a rise in private banks’ leverage, as their balance sheet composition switches away from government bonds and towards more credits (i.e. loans and securities). These actions push up Treasury term premia and, by lowering external financing costs they are associated with narrower corporate credit spreads, lower volatility, more real capital spending and faster economic activity. They may also reduce investors’ need to hold extra liquidity for precautionary reasons, assuming that the resulting mix of Central Bank assets boosts system-wide liquidity (i.e. by encouraging more risk-taking by banks and other credit providers). In short, LSAP could result in a reduced demand for safe asset Treasuries and an increased demand for both more duration and riskier corporate credits, thereby raising Treasury term premia and subsequently tightening corporate credit spreads and boosting equity prices. This matches the earlier time-series evidence following the Global Financial Crisis and the intuition that investors’ demands for safe and risky assets should move oppositely. In practice, the implementation of unconventional monetary policies was originally designed to bolster a then flagging US economy and so help defray both perceived and actual defaults and systemic risks. It would be, therefore, reasonable to conclude from a time-consistency perspective that a successful outcome would be faster nominal GDP growth and, hence, higher nominal Treasury yields and lower default risk premia embedded in corporate securities, and thus tighter corporate credit spreads.

These effects may also occur endogenously because changes in risk appetite could both be induced by liquidity factors and, in turn, stimulate future increases in credit provision. This makes it difficult to identify the *risk-taking channel* separately from the better known *credit channel*, not least because the latter depends on risk-taking by banks. Consequently, I set up a VAR to model the interactions and better understand the drivers of US Treasury term premia and corporate credit risk premia. Prime candidates for inclusion are measures of domestic and international liquidity and real economic activity. The literature review in Section 5.3 shows the importance of LSAP policies, but questions whether the monetary transmission channels can be restricted to Federal Reserve activity alone, because other large-scale transactors in asset markets also affect asset prices. My contention is that the impact of policy applies over longer time periods to broader liquidity measures that embrace shadow banks, repo markets and international capital flows and include the role played by government bonds as safe assets in business cycle recessions. Financial market imperfections, as reflected in term and risk premia, are central to monetary policy transmission. It seems plausible that improvements (deteriorations) in risk appetite, possibly induced by monetary expansion (contraction), lead investors to lengthen (shorten) and broaden (narrow) their investment horizons by moving into longer (shorter) duration and riskier (safer) assets, including real capital goods (cash). The latter, in turn, through traditional multiplier effects then influence the tempo of business activity. To analyse these dynamic interactions between monetary policy, expected market volatility, investors' risk aversion[54], leverage and credit flows, I build on the work of Bekaert, Hoerova and Lo Duca (2012) and Rey (2016). Like these previous studies, I analyse the dynamic links between the variables, but I also explicitly focus on the interplay between credit risk and term premia using the VAR framework.

The proposed vector auto-regression (VAR) contains both economic and financial variables (z_t) and follows the standard reduced form:

$$z_{t+1} = \Phi z_t + \Omega^{1/2}\varepsilon_t,\ \ where\ \ \varepsilon_{t+1} \sim NID(0, I_k)$$

and where Φ is a n × k autoregressive matrix and Ω is a n × k matrix. The vector of economic and financial variables (z_t) includes potential exogenous monetary policy variables (credit supply) and measures of investors' risk appetite; transmission

[54] Although, these terms are often used interchangeably, strictly *risk appetite* and *risk aversion* are not exact opposites (see Gai and Vause, 2006). I define risk aversion in terms of investor's preferences, while risk appetite derives from a combination of these preferences and macroeconomic conditions that indicate *riskiness*.

variables, such as risk premia (Treasury term premia, corporate credit spreads) and market volatility, and variables, that measure outcomes, such as business activity and inflation.

5.5 Data Description

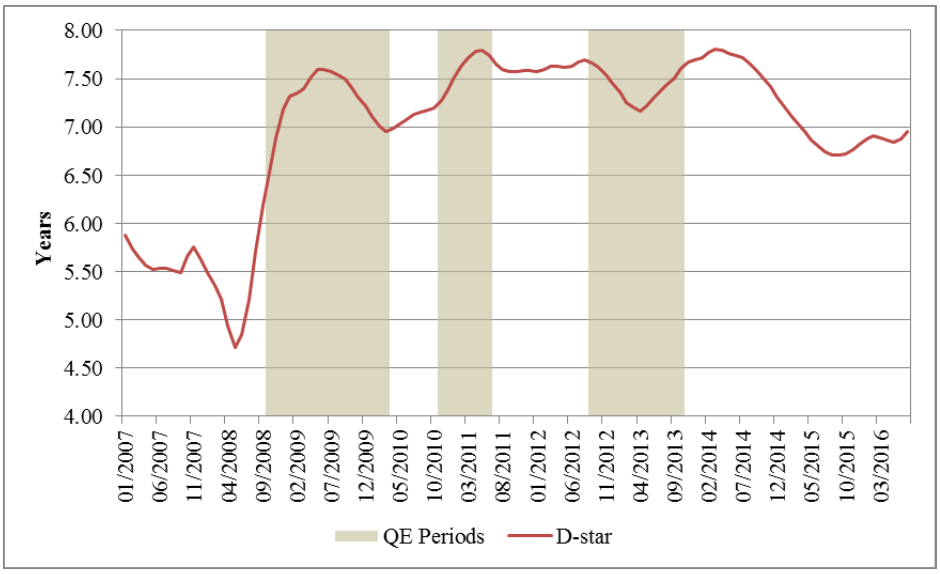
For monthly nominal Treasury term premia, I use the estimates at the 10-year maturity published by Adrian et al. (2014) and downloaded from the NYFRB website. Since this data series is not stationary according to an augmented Dickey-Fuller test (p=0.1212), I propose to also include in the VAR model a rolling three-year trend in US CPI (less food and energy) inflation. Evidence from Cieslak and Povala (2014) suggests that the effect of inflation on bond yields tends to be slow-moving and persistent. The corporate credit risk premia are calculated monthly from the spread between Bank of America/ Merrill Lynch single B high yield and BBB (Baa) investment grade bonds. These series are chosen in preference to CCC junk bonds for their longer available history. The Merrill Lynch MOVE index[55] of bond market volatility is included in the VAR model to measure bond *market liquidity* risk and to allow for the further effects that bond volatility may have on the risk appetite of credit providers. This index seems better-suited than the VIX for understanding the actions of credit-providers, who often hold large inventories of bonds as collateral. To capture the business cycle, I use the ISM Purchasing Managers' Index for US manufacturing industry. These variables were downloaded from the FRED website.

To model *funding liquidity* risk and the *credit channel*, I use the CBC Liquidity Indexes. These monthly data are published on-line (www.liquidity.com) and provide convenient and broad measures of US and International Liquidity. They have the advantage of providing a consistent quantitative measure of monetary policy than spans both the pre and post-GFC periods that, for example, unlike the Federal Funds rate is not compromised by the zero lower bound. Their construction follows the original recommendations of Gurley and Shaw (1960) by splitting money into its *inside* and

[55] MOVE is a weighted index of implied volatility for one-month U.S. dollar interest rate options across the yield curve. It is devised by Merrill Lynch and has been produced since 1988 as a bond market equivalent of the CBOE VIX index for stocks.

outside components. Here, *inside money* is defined to embrace financial institutions other than banks and to include net foreign activity. The data is based on the Federal Reserve's Flow of Funds (Z1) statistics, which cover a far-wider range of credit-providers, e.g. so-called *shadow banks*, than conventional money supply measures. For example, the stock of US liquidity, as defined in asset-terms, totals close to US$24 trillion in absolute size, or nearly double the circa US$13 trillion US M2 money supply. The index components allow a breakdown of US Liquidity into Federal Reserve, private sector and foreign sources. Index data are available for 80 economies and for several aggregates, such as *total emerging market liquidity*, which itself may influence Treasury demand given how many of these economies shadow the US dollar. The CBC indexes are reported in normalised data format and expressed as standard deviation units relative to a rolling 40-month mean. Since the CBC sub-index for Federal Reserve liquidity injections accounts for only one dimension of the LSAP, I also include the average maturity of the outstanding stock of Treasuries.

Figure 25: D-star (Implied Risk Appetite) and LSAP, 2007-16 (Monthly, Years)



Comment: The chart shows movements in D-star, the position of the curvature peak of the term structure (measured along the maturity axis). LSAP periods are shaded. D-star contracts from just over six years to 4.7 years ahead of the GFC. It bottoms and rises strongly through QE1 to over 7.5 years, remaining elevated, with only small fluctuations, through the subsequent QE2 and QE3 periods.

To capture investors' risk-taking behaviour, I use the D-star calculation derived in Chapter 3. This statistic approximates the demand for safe asset duration from the position of the curvature peak in the US Treasury term structure along the maturity/ duration axis. It is related to the maturity distribution rather than the size of term premia. D-star, averages 6.2 years (1946-2016) for the US, with a 10 month standard deviation. The data are stationary according to an augmented Dickey-Fuller test (p=0.000). The absence of a trend may indicate there is no long-term excess demand for or supply of safe assets. Figure 25 shows a monthly time-series plot of D-star over the recent LSAP periods, designated QE1, QE2 and QE3. D-star rises strongly through QE1 following the GFC: a time when risk appetite stood at extremely depressed levels. The data indicate that D-star bottomed prior to QE1, although the latter appears to reinforce its recovery. It also rises to a lesser extent through QE2, but actually falls coincident with QE3. Longer investment time horizons, i.e. higher D-star values, are associated with more risk-seeking behaviour by investors. I argue in Chapter 3 that intuitively this may be better understood from the special case of the quadratic yield curve, where the position of the curvature peak is mathematically related to the ratio between the slope and the curvature parameters. When both parameters move together, the curvature peak retains its position, but when the slope increases proportionately faster (slower) than the curvature, then the curvature peak, i.e. D-star moves rightwards (leftwards) along the maturity/ duration axis. Since curvature can also be explained by the duration effect of expected future interest rate moves, it will frequently correlate with the slope parameter assuming the 'normal' mean-reversion of interest rates. When rates are anticipated to rise (fall) significantly further, i.e. overshoot at cyclical economic extremes, then curvature will take on a smaller (larger) than normal value resulting in a larger (smaller) D-star value.

5.6 Estimation Results

Given the large number of variables deployed, I estimate a Bayesian VAR using monthly data from 1988-2016, incorporating a Litterman/ Minnesota prior. A lag length of three periods was chosen from the usual Likelihood Ratio and BIC criteria. The system is dynamically stable since all roots lie within the unit circle. A subset of the key impulse responses is shown in Figure 26. The complete set of generalised impulse response functions are reported in Appendix 5C, with equivalent results from a conventional VAR (with associated standard error bands) reported alongside. In general, the BVAR and the VAR give broadly similar results.

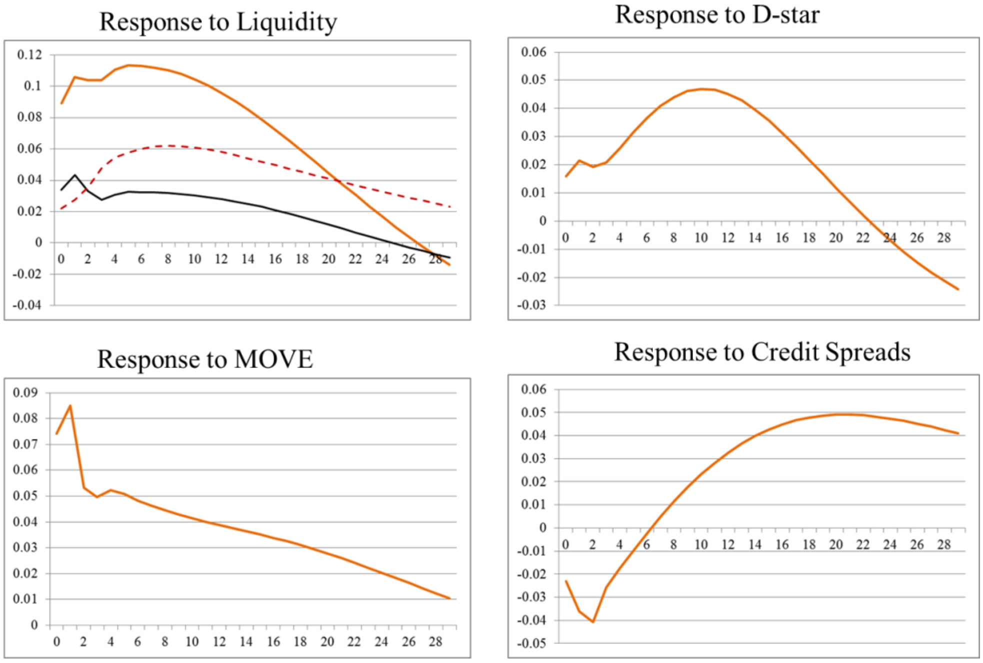
The upper four panels of Figure 26 illustrate the impulse response functions of 10-year Treasury term premia following shocks to risk appetite, liquidity and volatility. The liquidity impact is consistently positive with a peak after 10-12 months. The chart separately identifies the contributions from US central bank liquidity and emerging market liquidity: both are often large buyers of US Treasuries. The Federal Reserve initially has the stronger effect, but the liquidity impact from emerging markets on US term premia builds to a higher peak after 8-10 months. Following a shock to D-star (risk appetite) the response function quickly moves to a peak after around 10-12 months, before tailing off towards small negative readings two years out. Bond volatility (MOVE index) has an immediate positive effect on term premia, which then decays slowly over a two year period. Similar response functions are shown for credit risk premia in the lower four panels of Figure 26. In contrast to Treasury term premia, credit spreads tighten following liquidity shocks with a lag of 2-3 months and they appear to respond most to domestic private sector liquidity, possibly because this implies lower default risks. These asymmetric responses may help to explain the differential movements of term and credit risk premia between QE1 and QE2. The effect of D-star (risk appetite) on credit spreads evolves from positive to strongly negative after 10 months. The largest effect on credit spreads comes from a unit shock to the US ISM index (Purchasing Managers Index), which unambiguously causes them to narrow, probably again because corporate default rates implicitly decline. Credit spread shocks, themselves, correlate negatively with Treasury term premia up to seven months ahead, in line with 'Risk On' and 'Risk Off' moves. The other response functions look plausible (see Appendix 5C). For example, extensions in the average duration of outstanding Treasuries reduce bond volatility and the consumer inflation trend has a slightly positive impact on these risk premia.

The main findings from the BVAR can be summarised as follows:

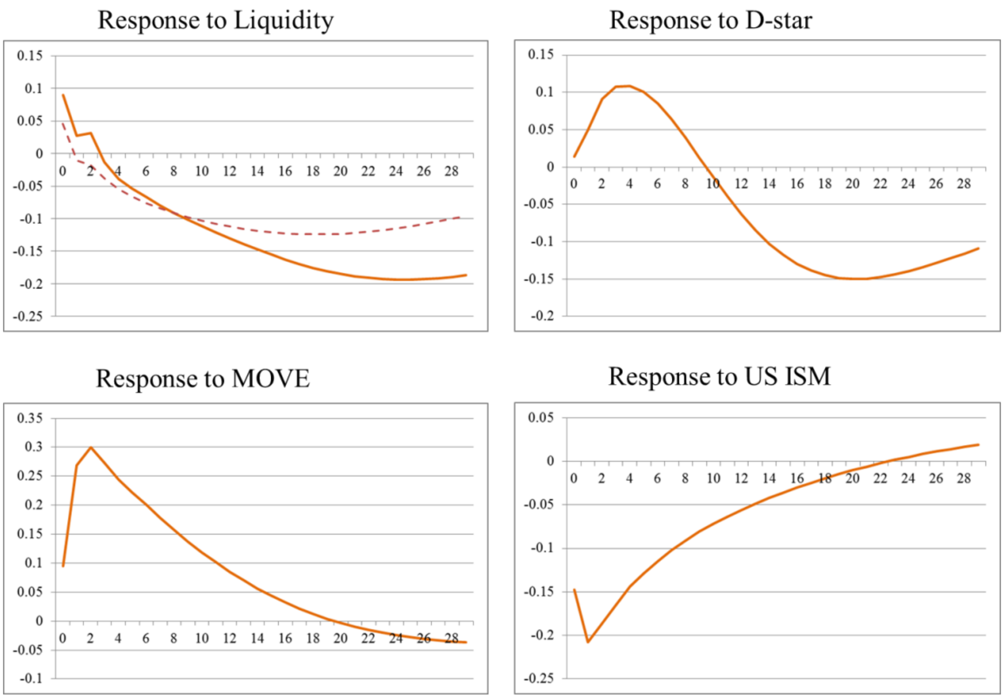
1) An increase in risk appetite (D-star) leads to higher Treasury term premia. These build to a peak at nine months, but turn negative after 22 months

Figure 26: Selected Impulse Response Functions (Periods)

Impulse Response Functions For US Treasury 10-Year Term Premium



Impulse Response Functions For US Credit Spreads



Comment: The upper four charts show the generalised impulse response functions over a 30-month time horizon for the Treasury real term premia following a unit shock to each of the four variables. The lower four charts describes the same for the credit risk premium. The broken line in the first chart denotes the response of Treasury term premia to an emerging market liquidity shock and the solid black line denotes the effect from a Federal Reserve liquidity shock. The broken line in the lower chart denotes the response of credit risk premia to private sector liquidity shocks.

2) An increase in the liquidity variables leads to a rise in Treasury term premia. This effect peaks at around six months. The impact coming from international liquidity (Emerging Markets) is strongest and Central Bank liquidity next strongest

3) Larger Treasury term premia lead to subsequently lower credit spreads, with the peak effect coming after 23 months

4) Credit spreads (B less Baa/ BBB) are shifted lower by an increase in the liquidity variables. Although spreads move perversely in the very short-term, they fall after a lag of four months and reach their minimums after 23 months

5) An increase in risk appetite (D-star) also causes credit spreads to initially rise, before reversing its effect and pushing them to lows after 19 months

6) An increase in the liquidity variables, notably private sector liquidity, improves risk appetite (D-star), with the effect peaking at 11 months

7) Increases in bond volatility and falls in credit spreads both positively impact Treasury term premia after one month

8) Increases in bond volatility (MOVE) and decreases in both the pace of US business activity (US PMI) and in the average maturity of Treasury debt all raise credit spreads after 1-2 months

9) Larger Treasury term premia are associated with stronger US economic activity (US PMI), with the peak effect occurring 20 months ahead

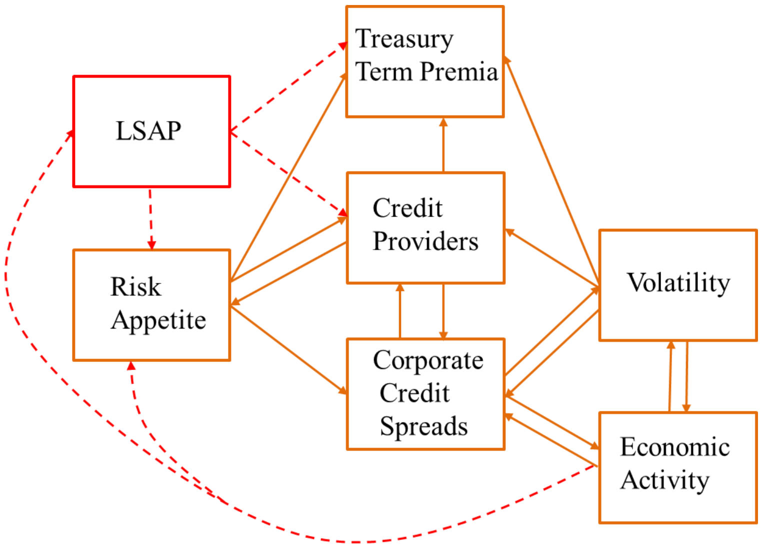
10) More abundant liquidity, notably Federal Reserve Liquidity, and greater risk seeking activity by investors and credit providers (D-star) both lead to positive impacts on US economic activity (US PMI), again with the peak effects coming after around 20 months

11) As risk appetite increases, the average maturity of Treasuries tends to fall, possibly indicating that the maturity of newly issued government debt responds to weaker demand for longer duration bonds

12) Central Bank liquidity responds positively to unfavourable shocks in risk appetite, volatility, economic activity and credit spreads

The BVAR results appear consistent with the interpretation that greater risk-seeking activity, possibly driven by an increase in LSAP and Federal Reserve liquidity injections or foreign buying of US Treasuries, leads to the portfolio substitution of safe Treasuries for riskier corporate credits. In parallel, risk-seeking private banks switch the composition of their balance sheets away from government bonds, towards more credits (i.e. loans and securities) and so take on higher leverage. This also aligns with the literature on looser private credit supply inducing falls in corporate bond risk premia. These actions push up Treasury term premia, but by lowering external financing costs they are associated with narrower corporate credit spreads, lower volatility, more real capital spending and faster economic activity. These effects appear to peak around 20 months ahead.

Figure 27: The Risk-Seeking Channel (Schematic)



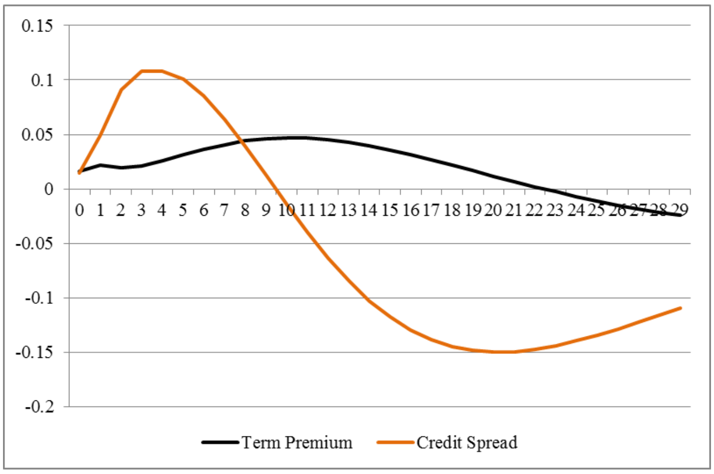
Comment: The chart describes the linkages between variables and illustrates the path of shocks to risk appetite and large-scale asset purchases (LSAP). The broken lines indicate the initial path of the LSAP shock and the subsequent feedback from changes to economic activity. The diagram shows several other feedbacks and emphasises the role of credit providers and the transmission through corporate credit spreads.

In turn, narrower credit spreads and lower volatility act as an accelerator mechanism by feeding-back into an earlier stage of the transmission chain, possibly through the relaxation of banks' internal VaR (value-at-risk) constraints. This adds to private sector leverage and liquidity, which raise Treasury term premia further, encourage additional risk-seeking and so reinforce the traditional *credit channel*. Larger Treasury term premia also tend to correlate with stronger international liquidity, possibly because this implies a net capital flow away from the US to emerging markets, which, in turn, could indicate returning 'flight' capital quitting safe US Treasuries. The BVAR results are also consistent with a fall in the average maturity of the outstanding private sector stock of Treasuries, leading to greater Federal Reserve liquidity, in line with the operation of LSAP. Figure 27 shows a schematic representation of the transmission mechanism indicated by the BVAR, where the solid lines indicate the many plausible paths of the risk-seeking channel. The main impacts from LSAP and the feedback effect from economic activity are highlighted as broken lines. According to a conventional VAR, the D-star measure of risk appetite is Granger causal (p=0.361), whereas other variables including policy liquidity do not appear to be.

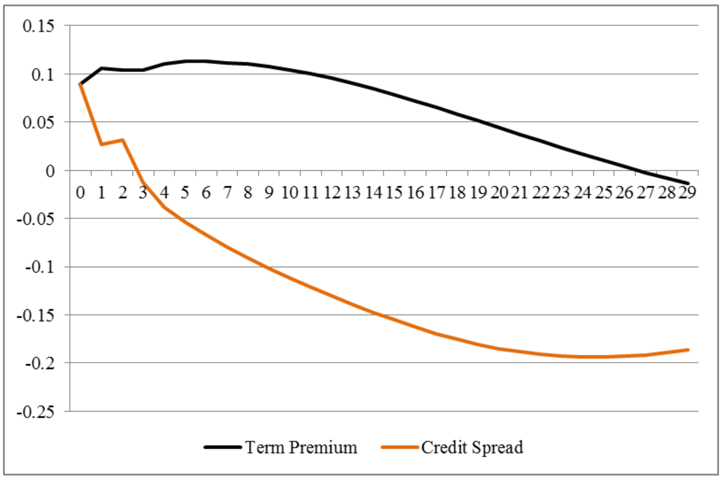
The comparative impulse response functions reported in Figure 28 show that the effects of 'liquidity' and 'risk appetite' (i.e. D-star) shocks are positively correlated: more liquidity as well as a larger D-star lead to higher Treasury term premia, and, unambiguously from 10-periods onwards, both shocks also cause corporate credit spreads to tighten. D-star appears to have the larger relative effect on corporate credit spreads, which is plausible assuming it signals greater risk-seeking behaviour. Equally, the liquidity factors seem to be more important for Treasury term premia, which is consistent in circumstances when more liquidity reduces perceived systemic risk, since investors should reduce their risk-avoiding investment strategies and switch away from Treasuries. It could, therefore, follow that US Federal Reserve 'Forward Guidance' policies have their greatest impact on corporate credit spreads, whereas LSAP programmes tend to initially push up Treasury term premia and only later cause corporate credit spreads to tighten.

Figure 28: Comparative Impulse Responses to D-star and Liquidity Shocks – 10-year Treasury Term Premia and B-BBB Credit Spreads (Periods)

(a) D-star



(b) Liquidity



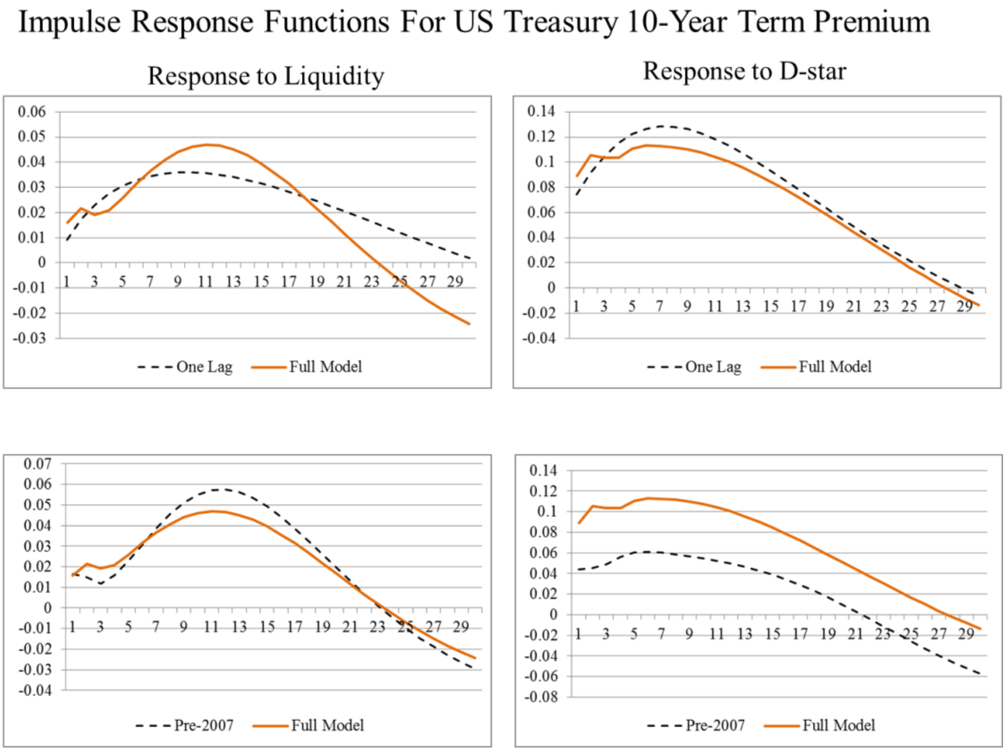
Comment: The impulse response functions taken from a BVAR model show the comparative responses over a span of 30 periods of 10-year US Treasury term premia and B-BBB corporate credit spreads to shocks in D-star (upper panel) and Liquidity factors (lower panel). Term premia seem to be most affected by changes in liquidity conditions, whereas credit spreads are in the first instance positively impacted by D-star (risk appetite), before a strong negative effect then takes hold. Between periods 4 and 20 following the shock, credit spreads tighten significantly.

I check robustness by re-estimating the VAR over the pre-crisis sample period 1988-2006 and by removing lags to ensure overfitting is not an issue. Figure 29 compares the impulse reponses for the 10-year term premia with those for the full model. The cross-check results do not alter my previous conclusions. However, I note that the effect of a D-star (risk appetite) shock is greater in the full sample that includes the GFC. This, in turn, may be because risk appetite became extremely depressed during the crisis. Four studies with a different focus, but some related results (Bekaert et al. 2012; Bruno and Shin, 2013; Rey, 2016, and Mallick et al. 2017) allow further robustness checks. Bekaert et al. (2012) extract a variance premium from the CBOE's VIX equity volatility index reflecting risk aversion[56]. They estimate a four-variable VAR that includes a business cycle indicator, the two VIX components and the U.S. Fed Funds target rate, inflation-adjusted. They find that a loose monetary policy reduces risk aversion (i.e. equivalent to my increase in risk appetite) and that periods of high VIX are followed by looser monetary policies. Bruno and Shin (2013) also run a four-variable VAR, using quarterly data over 1995-2007, but add measures of U.S. broker-dealer leverage and the real effective dollar exchange rate (i.e. this is similar to my inclusion of broader measures of liquidity). They find that a negative monetary policy shock leads to an increase in the VIX after four quarters and a decline in U.S. broker-dealer leverage after some two-and-a-half years. From a seven variable VAR, Rey (2016) similarly finds that a lower Federal Funds rate leads to falls in the VIX after about five quarters, while banks' leverage and gross credit flows rise after three years. In turn, a fall in the VIX leads to increases in global domestic credit, after one year, and greater bank leverage and capital inflows. Mallick et al. (2017) compute a seven variable VAR to study the explicit effects of monetary policy on volatility and the subsequent impact of any change in volatility on bond term premia. They find that an expansionary monetary policy reduces volatility and lowers term premia, but its effect on business activity in the post-GFC period becomes insignificant. Moreover, volatility shocks apparently raise term premia in the pre-GFC period and lower them in the post-GFC period, possibly because of a 'flight to safety'. Although all these four studies tend to report noticeably longer lag times, their conclusions seem compatible with my results since they collectively show: (1) the positive effect of liquidity factors on risk-seeking behaviour and (2) the importance of monetary transmission, via changing risk and term premia, along the *risk-taking channel*. The main structural differences between these studies and mine are: (i) my use of a larger 10-variable BVAR and adoption of a more recent dataset that includes the GFC; (ii) my focus on the joint interaction between the term and credit risk premia; (iii) my substitution of bond volatility (MOVE) for equity volatility (VIX); (iv) my inclusion of D-star to separately measure risk appetite, rather

[56] Variance risk premium(t) = $VIX_t^2 - E_t(\sigma_{t+1}^2)$, where σ_t is the realised return volatility on the S&P500 over 22 days

than taking the VIX or its derivatives, and (v) my use of variables that can better capture unconventional monetary policies, such as shadow bank credit, measures of Federal Reserve liquidity and cross-border capital flows.

Figure 29: Robustness Tests – Effects on IRFs of Dropping Lags and Restricting Sample Size



Comment: The upper two charts show the generalised impulse response functions over a 30-month time horizon for the Treasury real term premia following a unit shock to liquidity and risk appetite (D-star). The solid line denotes the full model and the broken line identifies the same model with lags restricted to one period. The lower two charts similarly distinguish between the full model (solid line) and a restricted sample (broken line), estimated prior to 2007.

Are these risk appetite and liquidity shocks economically-meaningful sources of variation in the financial cycle over time? A variance decomposition, using a Cholesky ordering, shows that while D-star only explains some 6 percent of the variation in Treasury term premia, it accounts for nearly 15 percent of changes to bond volatility, and for as much as 12 percent of the variations in both credit spreads and the US PMI business cycle over a 30-month time horizon. The aggregate liquidity variables determine over 12 percent of the variation in Treasury term premia; some 13 percent of the variation in credit spreads; nearly 10 percent of the change in bond volatility and over 8 percent of the variation in the US PMI. Thus, the combined impact of the risk appetite and liquidity factors on each of these four variables can account for between one fifth and a quarter of their overall variations. Although these shocks may or may not be correlated, which makes interpretation difficult, only 6 percent of the change in D-star appears to be explained by liquidity and just 13 percent of the change in liquidity comes directly from D-star. On the other hand, as much as 25 percent of the changes to policy liquidity are reactions to financial instability, such as wider credit spreads, larger term premia and greater bond volatility. A further noteworthy result is that while Treasury term premia only separately explain around 3 percent of the variation in credit spreads, credit spread shocks themselves determine nearly 16 percent of the variation in Treasury term premia and an even larger 30 percent of the variation in the US PMI. Bruno and Shin (2013) find that shocks to the Federal Funds rate explain almost 30 percent of the variance of the VIX at horizons longer than 10 quarters. In comparison, Bekaert et al. (2012) find that monetary policy shocks account for over 20 percent of the variance of risk aversion at horizons longer than seven quarters. Rey (2016) finds that shocks to the Federal Funds rate explain only around 4 percent of the variance of the VIX, but notes that the result is sensitive to the definition of leverage. Although there is some dispersion in these estimates depending on the number of variables and the exact specification of the VAR, they are all economically significant and potentially large effects. The results seem consistent with the interpretation that the liquidity and risk appetite counterparts of the LSAP are likely to have reduced the demand for safe Treasury securities and increased the demand for riskier corporate credits, thereby raising Treasury term premia and subsequently tightening corporate credit spreads.

5.7 Conclusion

Motivated by *event studies* of the post-GFC and Great Recession period, this chapter attempts to develop a better understanding of the policy transmission mechanism following LSAP. It distinguishes different risk premia channels for safe and risky assets; adopts a new measure of risk appetite rather than just taking stock market volatility, and includes broader definitions of liquidity. Like other studies, it shows: (1) the importance of a *risk-taking* channel; (2) the positive feedbacks between greater liquidity provision and lower risk, and (3) it specifically captures the positive policy reaction to heightened financial market instability. However, it differs, notably from many *event studies*, by (4) highlighting the opposite movements between US Treasury term premia and corporate credit spreads following LSAP programmes; (5) it points to variations in the efficacy of LSAP conditional of the state of risk appetite and the subsequent response of private sector liquidity, helping to shed light on why the policy impacts of QE1 appear greater than the subsequent QE2 and QE3, and (6) it suggests that the D-star measure of risk appetite, itself, is weakly Granger causal. These differences may arise because of shifts in the demand for Treasuries implicit in the calming and signalling (i.e. 'forward guidance') and cash injection dimensions of LSAP. Moreover, the observed statistical stationarity of D-star may tell us that there is no long-term excess demand for safe assets as some claim.

I specifically disagree with the widespread conclusion that LSAP lower and do not raise Treasury term premia and government bond yields. This claim is inconsistent with: (i) the time-series evidence; (ii) with the predictions from a Bayesian VAR model and (iii) from the likely long-run intensions of policy-makers (a notable time-inconsistency). In particular, the BVAR suggests that risk appetite is an important determinant of the financial cycle. It affects the leverage of global banks and subsequent credit growth (although I accept that my results above may show more statistical than economic significance), and ultimately changes Treasury term and risk premia. While close study of LSAP periods can improve our understanding of monetary transmission, event studies may be too one-sided insofar that they only consider the instantaneous effects of LSAP on a narrow range of Treasury issues and so ignore the possible long-term counter-trends and systemic effects, which may be better captured by a VAR. The definition of LSAP adopted by the event studies focuses on the one-off announcement effects on supply of several pre-selected Federal Reserve bond-buying programmes, rather than the broader systemic effects on demand that might include: (a) the impact from the simultaneous replacement of bonds with Central Bank or foreign investors' cash; (b) the cumulative expansion of Federal Reserve credit over the period and (c) feedback effects from changes in investors' risk appetite. While their emphasis on the reduced supply of safety acknowledges that US Treasuries are safe assets, the concomitant change in the demand for safety that may ultimately come to dominate is ignored, thereby missing the later downward pressure on Treasury prices. Thus, Krishnamurthy and Vissing-Jorgensen identify what they term a safety channel that should be more correctly seen as a scarcity effect, following Federal Reserve purchases of Treasuries from the private sector. These changes to risk-taking behaviour and in the demand for safety could be related to underlying changes in expected liability duration, and may possibly be induced, both by the knowledge that policy-makers are supportive (the bond market equivalent of the so-called 'Greenspan Put' in equities) and by the liquidity-boost counterpart from LSAP and the foreign-buying of Treasuries.

The *risk-taking transmission channel* ultimately involves a portfolio substitution of safe assets (e.g. Treasuries) for risky assets among investors (e.g. corporate bonds and equities) and credit providers (e.g. loans and securities), and includes feedback effects that amplify the original shocks through a more traditional *credit channel*. I show from a BVAR simulation that these combined transmission channels can account for between one fifth and one quarter of the overall variation in each of US Treasury term premia, B-BBB corporate credit spreads, bond volatility and the ISM US Purchasing Managers' Index. Variance decomposition suggests that the *risk appetite* variable has the greater impact on corporate credit spreads, whereas the liquidity effect from LSAP is a more important determinant of term premia. Yet, in practice the *credit channel* is hard to separately distinguish because when private banks extend credit they also take on more risk. It follows that the *risk-taking* and *credit channels* will often overlap. Overall, these channels dominate other LSAP effects such as scarcity of safe assets and lower duration risks. As investors' and credit providers' risk appetite improves and their investment time horizons lengthen, so Treasury term premia increase and the Treasury yield curve steepens, leading to falls in risk premia attached to other more risky instruments. Thus, as corporate credit spreads narrow, the relative prices of high yield (lower quality) corporate bonds are boosted. I conclude that as the attractions of risky assets improve, so the appeal of holding safe assets correspondingly diminishes. It follows that real-time asset markets alternate between 'Risk-On' and 'Risk-Off' states. The efficacy of unconventional policy actions appear greatest in these Risk-Off states, when risk premia are elevated and when LSAP can encourage or, at least, reinforce an improvement in investors' *risk appetite*.

Appendix 5A: Table 1, Major Actions and Statements Concerning Federal Reserve Large Scale Asset Purchases (LSAP) (Source: Engen et al, 2015)

11/25/2008 Federal Reserve Board announces its intention to purchase up to $100 billion in direct obligations of the housing-related government-sponsored enterprises (Fannie Mae, Freddie Mac, and Ginnie Mae) and up to $500 billion in GSE-issued MBS. These purchases are to be completed within several quarters. So called ‘QE1’.

3/18/2009 FOMC expands its asset purchase program to a total of $1.25 trillion in purchases of agency MBS, $200 billion in GSE obligations, and up to $300 billion of longer-term Treasury securities by the end-2009.

8/10/2010 FOMC states that it maintain its holdings of securities at their current level by reinvesting principal payments from agency debt and agency mortgage-backed securities in longer-term Treasury securities , and by continuing to roll over its holdings of Treasury securities as they mature.

11/3/2010 FOMC announces that, in addition to reinvesting principal payments from its securities holdings, it will expand the overall size of its portfolio by purchasing a further $600 billion of longer-term Treasury securities by the end of the second quarter of 2011. So called ‘QE2’.

9/21/2011 FOMC votes to extend the average maturity of its securities holdings by purchasing $400 billion of Treasury securities with remaining maturities of 6 years to 30 years and selling an equal amount of Treasury securities with remaining maturities of 3 years or less; these transactions are to be completed by the end of June 2012. The FOMC also announces that it will now reinvest principal payments from its holdings of agency debt and agency mortgage-backed securities in agency mortgage-backed securities, while maintaining its existing policy of rolling over maturing Treasury securities at auction.

6/20/2012 FOMC votes to maintain through the end of 2012 its ongoing maturity-extension program by continuing to purchase Treasury securities with remaining maturities of 6 years to 30 years at a pace of about [$45 billion per month] while simultaneously selling or redeeming the same amount of Treasury securities with remaining maturities of approximately 3 years or less.

9/13/2012 FOMC votes to begin purchasing additional agency mortgage-backed securities at a pace of $40 billion per month, in addition to continuing its maturity-extension program and its reinvestment of MBS principle payments in agency MBS. These actions imply increases in Federal Reserve holdings of longer-term securities of about $85 billion per month. The FOMC also states that if the outlook for the labour market does not improve substantially, it will continue its purchases of agency mortgage-backed securities, undertake additional asset purchases, and employ its other policy tools as appropriate until such improvement is achieved in a context of price stability, while also noting the size and composition of these purchases will take appropriate account of their likely efficacy and costs. So called ‘QE3’.

12/12/2012 FOMC announces that, after the maturity extension program ceases at the end of 2012, it will begin buying an additional $45 billion in long-term Treasury securities per month while continuing to purchase $40 billion in agency MBS per month and reinvesting principle payments, thus implying that the Federal Reserve’s portfolio will continue to expand at a pace of $85 billion per month.

3/20/2013, 6/19/2013, and 9/18/2013 FOMC refines its original guidance about the factors influencing the size, pace and composition of its ongoing asset purchase program by noting that it also depends on the extent of progress toward its economic objectives (March) and the inflation outlook (June). It also stresses that the pace of purchases is contingent on economic outlook as well its assessments of costs and efficacy (September).

12/18/2013 FOMC slows the ongoing monthly pace of purchases to $35 billion in agency MBS and $40 billion in long- term Treasury securities and advises that further reductions are likely at upcoming meetings if incoming information broadly supports the Committee's expectation of ongoing improvement in labour market conditions and inflation moving back toward its longer-run objective. However, the FOMC also stresses that asset purchases are not on a pre-set course but are contingent on the economic outlook.

Appendix 5A: Table 2, 'Forward Guidance' in FOMC Statements Issued From Late-2008 to 2013 (Source: Engen et al, 2015)

12/16/2008 After announcing a 0 to .25 percent target range for the federal funds rate, the Committee notes that "weak economic conditions are likely to warrant exceptionally low levels of the federal funds rate for some time." 3/18/2009 The Committee "anticipates that economic conditions are likely to warrant exceptionally low levels of the federal funds rate for an extended period."

11/4/2009 The Committee "continues to anticipate that economic conditions, including low rates of resource utilization, subdued inflation trends, and stable inflation expectations, are likely to warrant exceptionally low levels of the federal funds rate for an extended period."

9/21/2010 "The Committee will continue to monitor the economic outlook and financial developments and is prepared to provide additional accommodation if needed to support the economic recovery and to return inflation, over time, to levels consistent with its mandate."

8/9/2011 "The Committee currently anticipates that economic conditions (including low rates of resource utilization and a subdued outlook for inflation over the medium run) are likely to warrant exceptionally low levels for the federal funds rate at least through mid-2013."

1/25/2012 The Committee "… currently anticipates that economic conditions (including low rates of resource utilization and a subdued outlook for inflation over the medium-run) are likely to warrant exceptionally low levels for the federal funds rate at least through late 2014.".[57]

9/13/2012 The Committee "… expects that a highly accommodative stance of monetary policy will remain appropriate for a considerable time after the economic recovery strengthens" and "... currently anticipates that exceptionally low levels for the federal funds rate are likely to be warranted at least through mid-2015."

12/12/2012 The Committee "… expects that a highly accommodative stance of monetary policy will remain appropriate for a considerable time after the asset purchase program ends and the economic recovery strengthens. In particular, the Committee … currently anticipates that this exceptionally low range for the federal funds rate [0 to .25 percent] will be appropriate at least as long as the unemployment rate remains above 6½ percent, inflation between one and two years ahead is projected to be no more than a half percentage point above the Committee's 2 percent longer-run goal, and longer-term inflation expectations continue to be well anchored. The Committee views these thresholds as consistent with its earlier date-based guidance. In determining how long to maintain a highly accommodative stance of monetary policy, the Committee will also consider other information, including additional measures of labour market conditions, indicators of inflation pressures and inflation expectations, and readings on financial developments. When the Committee decides to begin to remove policy accommodation, it will take a balanced approach consistent with its longer-run goals of maximum employment and inflation of 2 percent."

12/18/2013 The statement reiterated the Committee's previously announced "action" thresholds for unemployment and projected inflation, and how its decision to begin tightening depend on a wide range of economic factors. In addition the Committee stated that it "… now anticipates, based on its assessment of these factors, that it likely will be appropriate to maintain the current target range for the federal funds rate well past the time that the unemployment rate declines below 6½ percent, especially if projected inflation continues to run below the Committee's 2 percent longer-run goal."

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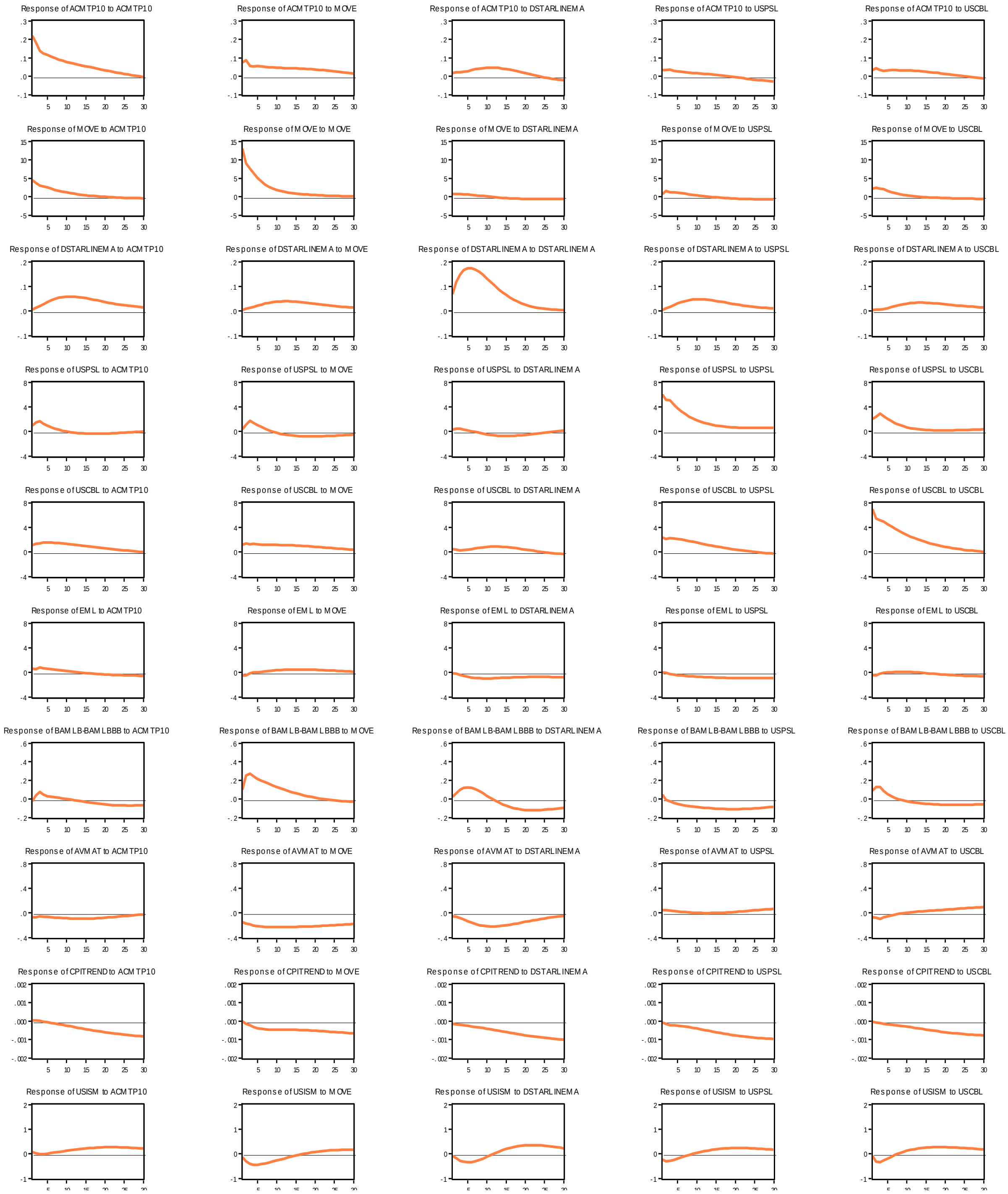
[57] In a separate statement released at the time, the Committee stressed that it would take a "balanced approach" in pursuing its dual objectives of price stability and full employment. The Committee also announced that agreement had been reached on a long-run inflation goal for PCE inflation equal to 2 percent. Because the rate of unemployment consistent with long-run price stability depends on factors outside the control of the central bank and needs to be estimated, no formal target was set for this leg of the dual mandate.

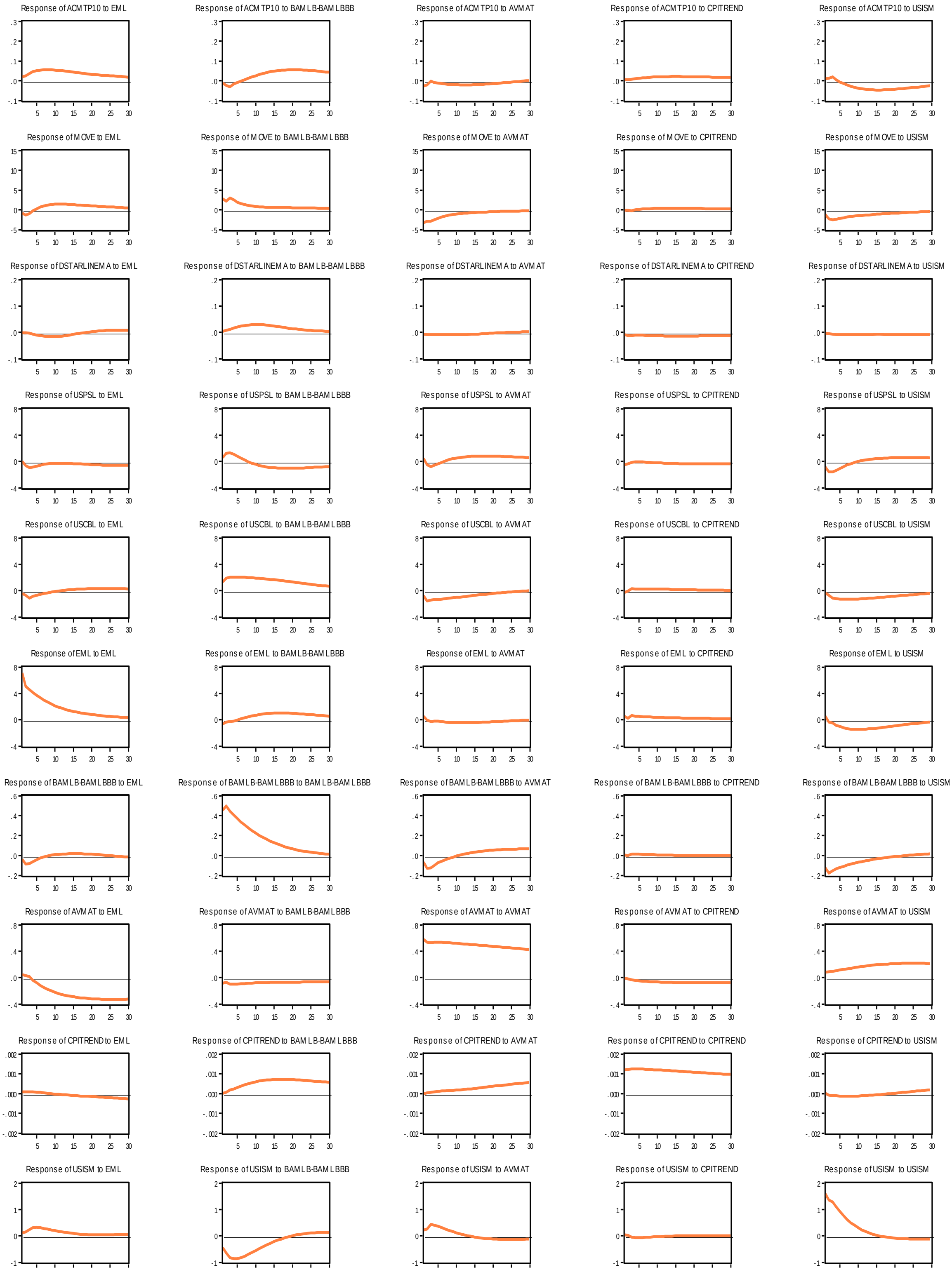
Appendix 5B: Impulse Response Functions

Figure B1.1: Bayesian VAR (BVAR) : Response to Generalized One S.D. Innovatio



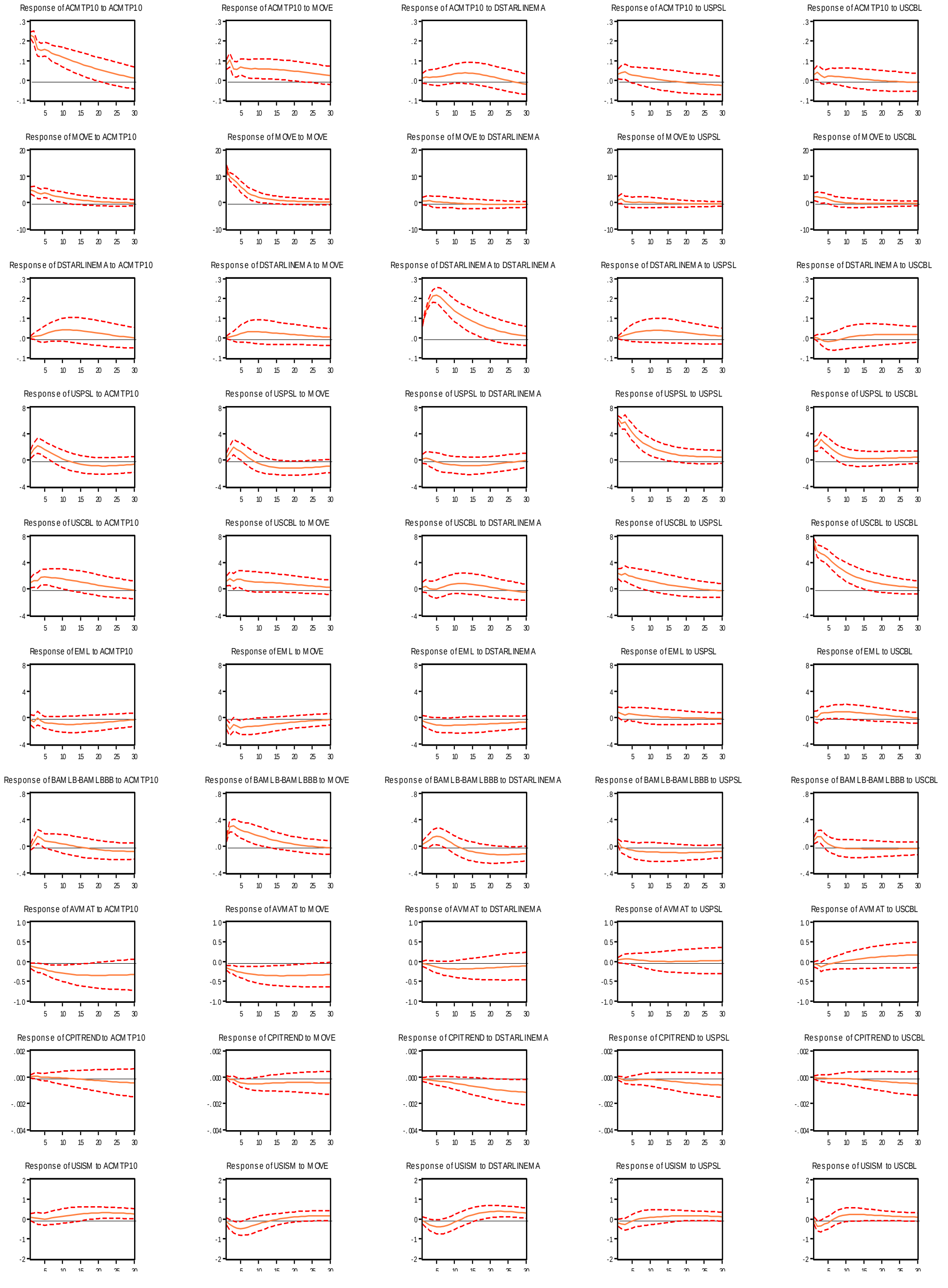
Panel (Figure B1.1) is the estimated impulse response functions from a Bayesian VAR with a Litterman/ Minnesota prior using monthly data over 1988-2016. Generalised responses are shown over a 30-month time horizon. DSTARLINE is the risk appetite variable, D-star; USISM is the ISM Purchasing Managers' Index; BAMLB-BAA is the high yield credit spread; ACMTP10 is the US Treasury term premia on the 10-year bond; AVMAT is the average maturity of outstanding US Treasury bonds; CPITREND is the 3-year trend in US Core CPI inflation; USCBL is the CBC index of US Federal Reserve Liquidity injections; USPSL is the CBC index of US domestic private sector liquidity creation; EML is the CBC index of Emerging Market Liquidity conditions; MOVE is the Merrill Lynch index of US bond volatility.

Figure B1.2: Bayesian VAR (BVAR); Response to Generalized One S.D. Innovations



Panel (Figure B1.2) is the estimated impulse response functions from a Bayesian VAR with a Litterman/ Minnesota prior using monthly data over 1988-2016. Generalised responses are shown over a 30-month time horizon. DSTARLINE is the risk appetite variable, D-star; USISM is the ISM Purchasing Managers' Index; BAMLB-BAA is the high yield credit spread; ACMTP10 is the US Treasury term premia on the 10-year bond; AVMAT is the average maturity of outstanding US Treasury bonds; CPITREND is the 3-year trend in US Core CPI inflation; USCBL is the CBC index of US Federal Reserve Liquidity injections; USPSL is the CBC index of US domestic private sector liquidity creation; EML is the CBC index of Emerging Market Liquidity conditions; MOVE is the Merrill Lynch index of US bond volatility.

Figure B2.1: Conventional VAR: Response to Generalized One S.D. Innovations + 2 S.E.



The panel (Figure B2.1) is from a conventional VAR estimated over the same period, with dotted lines showing 95% bootstrapped confidence intervals. Generalised responses are shown over a 30-month time horizon. DSTARLINE is the risk appetite variable, D-star; USISM is the ISM Purchasing Managers' Index; BAMLB-BAA is the high yield credit spread; ACMTP10 is the US Treasury term premia on the 10-year bond; AVMAT is the average maturity of outstanding US Treasury bonds; CPITREND is the 3-year trend in US Core CPI inflation; USCBL is the CBC index of US Federal Reserve Liquidity injections; USPSL is the CBC index of US domestic private sector liquidity creation; EML is the CBC index of Emerging Market Liquidity conditions; MOVE is the Merrill Lynch index of US bond volatility.

Figure B2.2: Conventional VAR: Response to Generalized One S.D. Innovations + 2 S.E.

The panel (Figure B2.2) is from a conventional VAR estimated over the same period, with dotted lines showing 90% bootstrapped confidence intervals. Generalised responses are shown over a 30-month time horizon. DSTARLINE is the risk appetite variable, D-star; USISM is the ISM Purchasing Managers' Index; BAMLB-BAA is the high yield credit spread; ACMTP10 is the US Treasury term premia on the 10-year bond; AVMAT is the average maturity of outstanding US Treasury bonds; CPITREND is the 3-year trend in US Core CPI inflation; USCBL is the CBC index of US Federal Reserve Liquidity injections; USPSL is the CBC index of US domestic private sector liquidity creation; EML is the CBC index of Emerging Market Liquidity conditions; MOVE is the Merrill Lynch index of US bond volatility.

Chapter 6

Concluding Remarks

The primary aim of this thesis is to better understand the term structure of interest rates. In their attempts to reduce the dimensionality of the term structure data, many researchers overlook the information content available beyond the standard three yield curve parameters. Not only do latest statistical analyses warn that the traditional principal component estimates of these parameters are unstable over time, but the testing climate of the 2007/08 Global Financial Crisis, when monetary policy was largely focused on Large-scale Asset Purchases (LSAP) of US Treasuries by the Federal Reserve, has found these traditional explanatory factors wanting. My conclusions seem closest to the recent research of Hanson, Lucca and Wright (2017). Unlike Adrian et al. (2014), they do not identify additional yield curve parameters. However, they point-out the instability of principal component methods and, like me, they argue against the claims made by the many recent event studies that LSAP lead to lower term premia and falling Treasury yields (Gagnon, 2016). In fact, as I show, rising term premia appear to consistently follow from these LSAP programmes. Ultimately, my explanation for this contra-wise move relies on a backwards shift in the demand curve for safe asset Treasuries at long maturities (drawn with respect to yields) induced by the associated liquidity injections, rather than, as they suggest, slow-moving arbitrage capital and the increasing elasticity in the demand curve for maturity. Although, I acknowledge that greater regulation has lately decreased the availability of arbitrage capital in the US fixed-income markets, the speed of even these reduced flows is still likely to be rapid.

My three key contributions lie behind this observation: (1) Measurement – I identify a fourth yield curve parameter, called D-star, that implicitly describes the cross-sectional pattern of term premia across tenors by measuring the position of the hump in the term structure along the maturity axis. This parameter is theoretically motivated by the preferred habitat model of Vayanos and Vila (2009) and by the 'gap-filling' model of Greenwood, Hanson and Stein (2010), to ensure that it does not appear *ad hoc*. (2)

Evaluation – Using estimates of D-star derived from a standard distance-measure, and later cross-checked for its robustness against Kalman filtered factors, I show that this new parameter adds value. Statistical tests demonstrate that it is Granger causal of a number of macro-finance variables that comprise standard financial stress indexes (FSIs); Bayesian Information Criteria (BIC) indicate that it can predict these same key variables some 12-15 months ahead; out-of-sample forecasting tests demonstrate that it delivers a lower mean-squared error (MSE) than its benchmark, and it performs respectably in two recent event studies. (3) Transmission – Taking D-star as a measure of investors' risk appetite makes it easier to track-down the effects of quantities on the shape of the yield curve. D-star specifically helps to better understand recent policy transmission through the *risk-taking* channel of Adrian and Shin (2010); Borio and Zhu (2012), and Bruno and Shin (2014). My intuition is that LSAP programmes are multi-faceted and embrace scarcity and duration effects, as well as more powerful signalling and liquidity effects that ultimately induce a shift in the demand curve for safe asset Treasuries as investors' fears of systemic risk reduce. These latter liquidity effects overlap the *risk-taking* and traditional *credit* policy transmission channels. They constitute part of the wider liquidity effects coming from domestic and foreign credit providers (Adrian, Moench and Shin, 2010, and Rey, 2016). I attempt to quantify their impact using a Bayesian vector-autoregression (BVAR) model, similar to Rey (2016). The BVAR simulation shows how these combined transmission channels account for between one-fifth and one-quarter of the overall variation in each of US Treasury term premia, B-BBB corporate credit spreads, bond volatility and the ISM US Purchasing Managers' Index. A variance decomposition suggests that the D-star *risk appetite* variable has the greater impact on corporate credit spreads, whereas the liquidity effect from LSAP is a more important determinant of term premia. I conclude that the efficacy of unconventional policy actions appear greatest in so-called Risk-Off states, when risk premia are elevated and when LSAP can encourage or, at least, reinforce an improvement in investors' *risk appetite*.

I suggest that this research can take three future directions. First, there is an obvious task to calculate and test equivalent D-star values for other international fixed-income markets. These calculations could extend to index-linked as well as conventional nominal bond markets, and, where they exist, also to corporate as well as government bond term structures. Second, the statistic I devise to calculate D-star is a practical compromise that must be put into the context that reliable estimates of term premia are not yet widely available. A more robust measure of D-star must be a goal, but this in turn ultimately requires better estimates of term premia and, by implication, better term structure models. Third, this research has a number of clear policy implications that can be further explored. The recent event study literature concludes that LSAP programmes reduce Treasury yields. Although I note that this outcome is both questionable and not time-consistent with policy-makers long-term aspirations, the conclusion is still often acknowledged as fact. This demands a better understanding of the policy transmission mechanisms. However, in the meantime D-star can still be usefully employed as one of the array of indicators monitored by policy-makers to warn of upcoming financial stress.

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