When is the supply effect large in the government bond market?

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Job Market Paper

Abstract

I examine the time-varying impact of the US Treasury debt supply on bond risk premiums. I find that the elasticity of bond risk premium with respect to supply depends on the correlation between stock and bond returns. An increase in the supply of Treasury bonds raises the required bond risk premiums, but the effect is stronger as stock and bond returns become more positively correlated. I interpret this evidence within the context of a preferred-habitat asset pricing model where the arbitrageurs are the marginal investor for all bond maturities. Arbitrageurs demand higher compensation for maturity risk when the stock-bond correlation is positive as bonds are poor hedges for stocks. On the other hand, when the correlation turns more negative, an increased bond supply induces low or even negative risk premiums. The findings have practical implications for understanding the impact of the impending Federal Reserve's unwinding of its $4.5 trillion bond portfolio.

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With the U.S. Federal Reserve's decision to unwind its Large-Scale Asset Purchase program and Congress's tax reform, there will likely be big changes to the supply and maturity structure of the US government debt.[1] Market participants among others are keenly interested in how these changes will affect interest rates, asset prices and the economy. Many studies since the recent financial crisis have reported that increasing the Treasury supply, either by an increase in the dollar value or a lengthening of the duration of the bond portfolio held by the private sector, will raise the expected returns of government bonds.[2] However, researchers that have looked at the long time series evidence generally assumed a constant demand elasticity for bonds. I provide new evidence in this paper that the demand curve for Treasury bonds has shifted significantly over time, which in turn affects the strength of the Treasury supply effect.[3]

I show, both empirically and theoretically, that the more positive the correlation between stock and bond returns, the more bond risk premiums rise in response to an increase in the Treasury supply. These empirical findings are surprising from the perspective of standard asset pricing theory, in which there is no role for demand and supply factors.[4] Greenwood and Vayanos (2014) lay out a preferred-habitat asset pricing theory to show how supply may affect bond prices and risk premiums. Yet, their model only has bonds in it and does not allow state-contingent supply effects. I enrich and extend the Greenwood and Vayanos study by adding stocks to the set of investable assets and rationalize the new empirical facts. Intuitively, if bonds and stocks are negatively correlated then bonds are a good hedge for stocks and investors will be willing to absorb the increase in supply. The "demand curve" will be flat and the response of risk premiums will be small. If bonds and stocks are positively correlated, then bonds are risky. Investors will need to be compensated for taking on additional risk that accompanies the increase in supply. Demand will be less elastic and risk premiums will

[1]On July 6, 2017, Richard Koo, the chief economist of Nomura bank, observed that the QE unwind will be economically equivalent to issuing new Treasuries to finance fresh deficits. When the Fed stops reinvesting principal payments from maturing Treasury securities, the U.S. Department of Treasury Department will have to pay the bonds' face value to the Fed. Since the federal government is not running a surplus, this is money that the Treasury does not have. The Treasury will then have to market new Treasuries to private investors to fund the Fed's redemption. (*FT Alphaville*)

[2]See D'Amico and King (2013), Greenwood and Vayanos (2014), and Gagnon (2016) for surveys of the theory and empirical estimates for the Treasury supply effects.

[3]Because a supply effect is the result of a movement along an imperfectly elastic demand curve, time-varying supply effects and time-varying demand elasticities are equivalent.

[4]For these factors to matter, there needs to be some degree of market segmentation or imperfect asset substitutability.

need to rise more per unit of supply.

The stock-bond correlation affects the sensitivity of the bond risk premium to Treasury supply because it tracks the hedging ability of government bonds over time. Campbell, Sunderam and Viceira (2017) document that stocks and bonds were positively correlated prior to 1999 and negatively correlated thereafter. Consistent with my theory, I show that the risk premiums respond more aggressively to changes in supply during the earlier period than they do in the latter period. Campbell et al further show theoretically that an increasing stock-bond correlation, which indicates a higher covariance between nominal and real assets, leads to a higher bond risk premium. Specifically, they interpret the changing stock-bond correlation more fundamentally as a change in the covariance between inflation and the real economy. As inflation goes being bad news for real output growth to good news over the last 30 years, nominal bonds have also become better hedges for stocks.[5] Therefore, while the supply factor and the covariance risk have separately been identified as drivers of the bond risk premium, this paper highlights the fact that the two driving factors actually reinforce each other.

In the main body of the paper, I discuss the empirical evidence before presenting a theoretical model that helps us understand the empirical facts. I provide empirical evidence by regressing bond risk premiums on the new bond supply using data from 1961 to 2016. The bond risk premium is the difference between the long-term bond yield and the average short-term interest rate that investors expect to prevail during the life of the bond. It is typically interpreted as the compensation for holding long-term bonds and withstanding interest rate risks. Since market expectations are not directly observable, bond risk premiums are also unobservable and must be estimated. In the baseline regression, I employ a popular off-the-shelf bond risk premium measure from Adrian, Crump and Moench (2013), who gauge expectations statistically by estimating an affine term structure model on bond yields. I construct the bond supply measure with new issuances over the following 12 month period. Specifically, the bond supply is defined as the maturity weighted total face value of issuance divided by the nominal GDP.[6] I find that while unconditionally there is a positive relation

[5]Piazzesi and Schneider (2006) make a similar observation that the compensation for the inflation risk of nominal bonds should depend on the extent to which inflation is perceived as a carrier of bad news.

[6]I will discuss in greater details below why I choose to focus on issuances rather than the entire stock of debt. It suffices to say that the result is robust to using the stock of debt.

between bond risk premiums and supply, it is not statistically significant. When I control for the correlation between stock and bond returns, the supply effect becomes both stronger and statistically significant. Moreover, there is also a positive and statistically significant coefficient on the interaction term between the supply and the stock-bond correlation. This indicates that the supply effect is stronger when stock and bond returns are more positively correlated or when bonds are poorer hedges for stocks.

The regression has a causal interpretation if the supply measure is exogenous to bond risk premium shocks. However, clearly the quantity of government debt supply does respond to risk premium shocks (e.g., business cycle risks). Treasury issuances closely follow deficits, which are highly countercyclical. The maturity-weighted issuance to GDP ratio is mechanically the product of the weighted average maturity of the issuance portfolio and the issuance to GDP ratio. As a result, the supply measure, like the deficit to GDP ratio, should rise during a recession and fall during an expansion. On the other hand, the required risk premiums near business cycle troughs are high and low near the peaks. Therefore there is a natural endogeneity in the regression. I address the endogeneity issue by instrumenting for the supply measure with the weighted average maturity of issuance while controlling for the quantity of debt. The empirical results remain quantitatively similar. The weighted average maturity (WAM) of issuance is a valid instrument because the government's maturity choice in the short run is exogenous of market bond prices. Indeed, Garbade and Rutherford (2007) and Hou (2017a) document that the Treasury manages its issuance and repurchases to achieve a target maturity of the outstanding debt. It does so by issung a balanced amount of Treasury bonds across the maturities while tilting toward the long maturities only when the debt to GDP ratio rises.[7]

To formally articulate the theoretical intuition behind the empirical results, I present a modified preferred habitat term structure model. There are two types of agents in the bond markets: the preferred habitat (PH) borrowers and the risk-averse arbitrageurs/investors (Arb). The PH borrowers, which the U.S. Treasury is one by assumption, have a certain maturity preference for their debt issuance and are relatively insensitive to interest rates.

[7] Bhandari et al. (2017) shows theoretically that this policy is actually optimal as in it maximizes social welfare. In fact, since 1970 the Treasury has made an explicit commitment to a "regular and predictable" issuance schedule and eschews "tactical issuances".

For example, the US Treasury, for the purpose of maintaining market liquidity and others, have a preference for issuing a balanced amount of bonds across the maturities rather than concentrating issuance in the maturity with the lowest interest rate. The Arb investors, on the other hand, seek to maximize the mean-variance of the portfolio returns, comprising stock, bond, and the risk-free rate returns. If the only available assets are bonds and the risk-free asset, the Arb investors demand risk premium for absorbing the net supply of bonds as compensation for taking on additional durational risk.

In my model, I make a key assumption that investment capital moves slowly across asset classes. One way to think about this assumption is as follows. Institutions that perform the arbitrageur role (e.g., the trading desks or the hedge funds that rely on funding from brokers), are part of a business that is intrinsically exposed to stock market risk (or business cycle risk for each the stock market proxies).[8] These firms cannot easily shed their exposure to stocks without exiting their business. Therefore under this assumption, the Arb investors, unable to quickly adjust stock positions, must evaluate the additional durational risk of the new bonds against their hedging value for stocks. If the bond returns positively co-vary with stock returns, the required bond risk premium will be the sum of the duration risk compensation and the covariance risk compensation. The covariance risk premium increases with the risk aversion of the Arb investor, as well as the quantity of stocks held by the Arb investor.

1 Literature Review

This paper belongs in a nascent literature on the effects of demand and supply factors in asset markets, which is a part of the larger limits-of-arbitrage literature. It also nests in a literature that tries to connect the bond risk premium with fundamental economic drivers. In the first category, because my paper is the first to identify a time-varying supply effect, the closest papers are those on the effects of demand and supply shocks in bond markets. Motivated by the policy implications of quantitative easing, there is a strand of literature on

[8]Duffie (2010) was the first paper to investigate the implications of the slow movement of investment capital. Greenwood, Hanson and Liao (2017) build a preferred habitat model with slow-moving capital across asset classes where they allow the Arb investor to partially adjust their portfolio allocation. They find asset prices exhibit an overreaction to supply and demand shocks in the short run that dissipates in the long run. In that spirit, our papers have a similar stance on market structure.

the effects of changing the supply or the composition of privately held Treasury securities. Greenwood and Vayanos (2014), which is the closest to this paper, writes down a preferred habitat model and empirically shows that increasing the supply of Treasury securities raises bond yields and bond excess returns. However, Greenwood and Vayanos only consider bonds and do not investigate the time-varying properties of the supply effect. Greenwood, Hanson and Liao (2017) consider a model of partial market segmentation and limited arbitrage and demonstrate theoretically how demand and supply factors can lead to "overreactions" of asset prices. The theoretical environment of their paper is very similar to this paper's, but their paper still only deals with the "level" of the supply effect and not the sensitivity of the supply effect to higher moments of asset returns. Hamilton and Wu (2012) structurally estimate a discretized version of the GV model and find that a measure of Treasury supply is predictive of excess bond returns. A few researchers also examine the effects of the flow measures of supply. Beltran et al. (2013) use an instrumental variable approach to estimate the impact of foreign capital inflows into the U.S. Treasury market on long term yields and find that a decrease in foreign inflow raises long yields significantly. D'Amico and King (2013) use the GV model as motivation to estimate the response of the Treasury yield curve to QE1 purchases. My paper is also related to a strand of the macro-finance literature that tries to link bond risk premiums with macro fundamentals. Ang and Piazzesi (2003), using an affine term structure model with fundamental factors, finds that a significant portion of the variability of the yield curves is explained by unobserved latent factors. Ludvigson and Ng (2009) apply dynamic factor analysis to a rich set of factors and finds macro fundamental factors are essential for explaining the (counter-)cyclicality of bond risk premiums.

2 Data and Measurements

In this section, I describe the data sets used in the study and the construction of the key variables. The data sources are described in the section 2.1. In section **??**, I describe how I construct the three main variables used in the empirical analysis.

2.1 Data Sources

I use three types of data in this paper: 1) the historical data on the portfolio of outstanding Treasury securities from 1958 to the present, 2) zero coupon interest rates and estimated bond risk premium time series data and 3) other macroeconomic time series data.

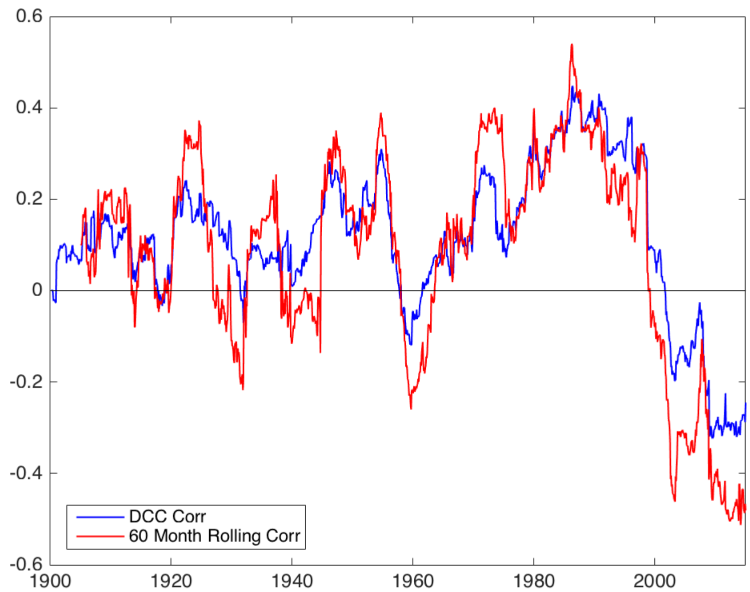
I obtain the historical data on the US Treasury debt primarily from the CRSP Treasury database for the years from 1958 onwards. The dataset contains monthly snapshots of all Treasuries outstanding including bond prices, security issue characteristics as well as other special features. CRSP obtains the Treasury quantity and issue information from the Monthly Statement of Public Debt (MSPD), which is publicly available from the Treasury website. The CRSP datasets contain numerous instances of entry errors (especially on quantity outstanding) and other mistakes. I manually verify the CRSP datasets against the MSPD records and manually correct any mistakes. The bond prices in CRSP are obtained from either GovPX or the New York Fed, as detailed in the CRSP Treasury manual. I supplement the CRSP Treasury dataset with data prior to 1958 by manually inputting the quantities of the marketable securities from the MSPD. I also obtain bond prices from the archival records of *the Wall Street Journal*.

The interest rate-related data can all obtained from the Federal Reserve Board website. Specifically, I use zero coupon bond yields that are estimated by Gurkaynak, Sack and Wright (2006). The bond risk premium series are taken from from Kim and Wright (2005) and Adrian, Crump and Moench (2013). These three data series are maintained and updated daily on the Federal Reserve board website. In addition, I also regenerate the ex ante holding period return measure of the bond risk premium from Cochrane and Piazzesi (2005). Cochrane and Piazzesi use the Fama-Bliss bond yields that are available from the CRSP Treasury data base.

The rest of the macro time series data comes from either Global Financial Data (GFD) or the FRED databases. For the calculation of the stock- bond return correlation, I use the S&P 500 total return index and the 10-Year Treasury bond return index series from the GFD database. All other macroeconomic time series, such as nominal GDP or inflation, are downloaded from the FRED.

2.2 The Correlation Between Stock And Bond Returns

Figure 1: Correlation of Stock and Bond Monthly Returns: 1900-2016



The correlations are obtained from the S&P 500 total return index and the Treasury 10 year bond index at five year moving windows. The data comes from Global Financial Data Inc.

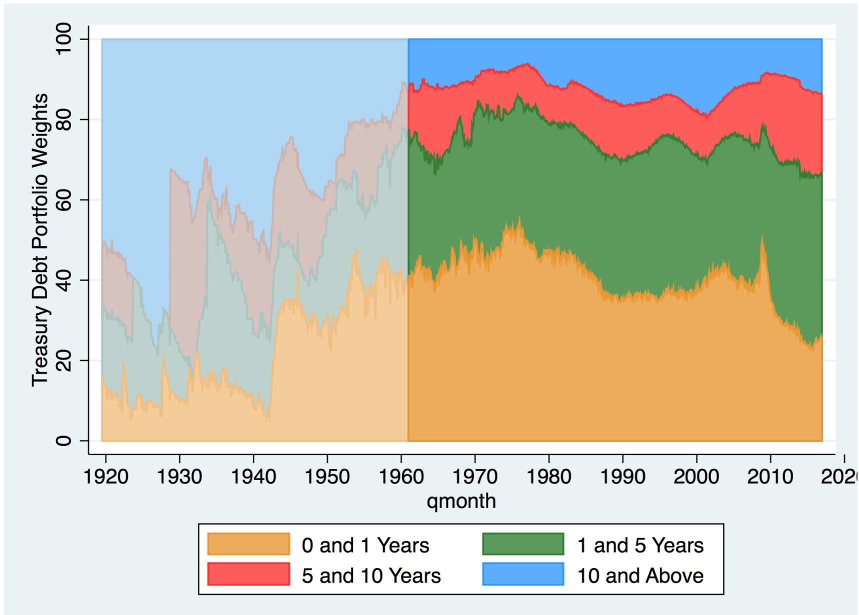
The stock-bond return correlation is the key state variable in this paper that reflects the investors' time-varying demand for Treasury bonds. A simple and nonparametric way of constructing the correlation is by calculating a 60 month moving realized correlation between the monthly total returns of the S&P 500 Index and the monthly returns of a 10 year Treasury bond. Figure 1 depicts the evolution of this correlation over the last 100 years. The stock and bond correlation is highly persistent but has experienced several abrupt sign flips, notably mid 60s and late 90s. Some researchers attribute the abrupt sign changes to the sharp rise Contrary to the conventional financial advisorial wisdom that stock and bonds are inherent risk hedges, they have actually moved in tandem more often than moving in opposite directions.

A chief concern about using a simple moving window correlation is that it ignores the autocorrelation and heteroskedasticity of returns. Stock returns, and to a lesser extent bond returns, are known to have a generalized autoregressive conditional heteroscedastic (GARCH) type of volatility. The persistence of monthly stock-bond correlation can be a result of autocorrelated volatility. I address this concern by estimating correlation using the dynamic conditional correlation (DCC) method proposed in Engle (2002). In this approach, I model stock and bond returns as a multivariate GARCH (1,1) process. I find that the 60 month moving correlation is not that different from the DCC estimates. They are highly correlated. As shown in Figure 1, between 1905 and 2016 the two estimated series have a correlation of 92.1% and since 1961 they are 95.4% correlated. To generate the baseline results, I use the DCC measure. It is perhaps unsurprising that the empirical results are very similar using either the simple moving window correlation or the DCC measure.

In this paper, I do not investigate the fundamental drivers of the stock-bond correlation. I only point out its importance and usefulness as a state variable. However, given its centrality in the paper, I would be amiss not to discuss the likely drivers of the variable and how the bond supply effect is related to these more fundamental drivers. There is a paucity of literature that on the stock-bond return correlation. In the asset pricing literature, stocks and bonds are typically priced separately. In the smaller but resurgent portfolio choice literature, higher moments like the variance and covariances of asset returns are typically assumed to be constant. (Brandt (2010)) A notable exception that tackles this topic is Campbell, Sunderam and Viceira (2017), who argue that the stock-bond correlation is driven by the evolving relation between (permanent and temporary) inflation expectations and the real economy. They use the stock-bond correlation to obtain information about the correlation between real and nominal assets (and between real activity and inflation), which in turn cause time variations in bond risk premiums. Campbell et al. focus on the inflation risk premium component of the BRP, whereas I focus on the supply risk premium component whose time variations are driven by the covariance risk of bonds. Li (2002) analyzes the stock-bond correlation in a statistical asset pricing model and identifies expected inflation uncertainty as the primary driver. Piazzesi and Schneider (2006) also identify the relation between inflation and the real economy as an important factor. They show in a general equilibrium model with recursive consumer preferences that the negative covariance between inflation and real growth news gives rise to an upward sloping nominal yield curve and significant bond risk premiums.

2.3 Measuring The Supply of Treasury

Figure 2: Evolution of the Treasury Debt Portfolio 1920-2016



Treasury supply is defined as a maturity-weighted sum of new issuances (MWI) normalized by the nominal GDP. Unlike many papers in the literature that treat the outstanding stock of U.S. Treasury debt as supply, I view the new issuances as a superior gauge of the Treasury's debt supply policy. Because the U.S. Treasury has rarely bought back its debt or exercised early redemption, it primarily exercises control over its debt portfolio by adjusting its new issuances. From the market's perspective, the new issuances are also most relevant for the adjustments of arbitrageurs' portfolios. This is particularly true for long-term bonds because older bonds are normally shelved and held through maturity by long-term investors. Most of the trading in the bond market is on the newer issues. Older bonds are less frequently traded and relatively more illiquid.[9]

For new issuances, I include all new debts issued in the following 12 months. I measure issuance "forward" or near-future issuances because Treasury issuances are normally well telegraphed to the market ahead of time.[10] Therefore, it is reasonable to assume that the

[9]Krishnamurthy (2002) documents that the Treasury bonds that have been issued for some time tend to have a discount compared to newly issued bonds of the same time to maturity. He attributes the price difference to the difference in liquidity quality between old and new bonds.

[10]The Treasury Department holds quarterly meetings with the Treasury Borrowing Advisory Committee

bond market reacts to (expected) issuances as news shocks. By the same token, the regression in its baseline setup is not a predictive regression unless market anticipations of near-term Treasury issuances are perfect. For robustness, I move the issuance window backward and forward a few months, and the results are not qualitatively changed.

The formula of supply is as follows:

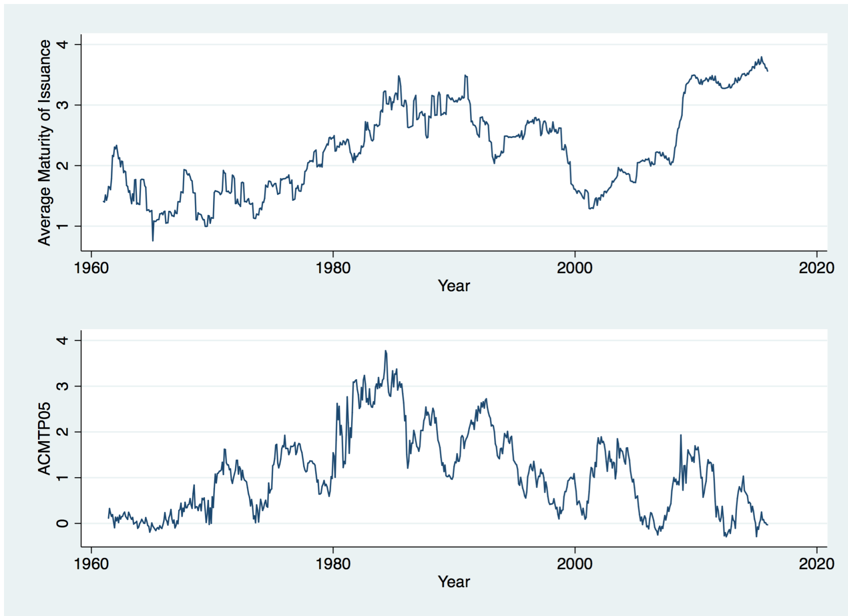
$$\begin{aligned} MWI_t =& \frac{\sum_{\tau, t \le s \le t+12} \text{FVOIss}_s^\tau \cdot \tau}{NGDP_t} \\ =& \frac{\sum_{\tau, t \le s \le t+12} \text{FVOIss}_s^\tau \cdot \tau}{\sum_{\tau, t \le s \le t+12} \text{FVOIss}_s^\tau} \cdot \frac{\sum_{\tau, t \le s \le t+12} \text{FVOIss}_s^\tau}{NGDP_t} \\ =& WAM_t \cdot \frac{\text{Total Issuance}_t}{NGDP_t}. \end{aligned} \tag{1}$$

In the second equality, I decompose MWI into two terms: the weighted average maturity of new issuances and the total issuance as a share of GDP. This decomposition highlights the two different ways in which supply may be increased: 1) increasing the WAM while keeping the quantity of supply to be absorbed constant; 2) increasing the quantity of supply outright as a share of the nominal GDP. Since the deficit to GDP ratio is known to be countercyclical, one way to resolve the endogeneity issue is by instrumenting the MWI measure using the WAM of issuance. The issuance to GDP ratio reflects business cycle risks, the WAM of issuance mainly reflects the Treasury issuance policy.

This instrument is valid if the Treasury's short-term issuance policy is exogenous to shocks to bond risk premia. I argue that this is indeed the case. Garbade (2007) explains that the Treasury follows a "regular and predictable" auction schedule and does not engage in "tactical issuance" or "market timing." Hou (2017) documents that the Treasury issuance has historically been driven by a desire to maintain stability of its portfolio rather than as a myopic objective of borrowing at the cheapest maturity. Indeed, Bhandari et al. (2017) use a theoretical model to show that the optimal Treasury issuance policy is one that issues evenly across the maturities, with a tilt towards the long term debt when the debt to GDP ratio is high.

(TBAC), consisting representatives from Primary Dealers in the Treasury market, to gauge demand and solicit issuance recommendations.

Figure 3: Plots of WAM of Issuance and 5 Year Term Premium



WAM_issue is the weighted average maturity of new issuances in the next two 12 months. ACMTP05 is the zero coupon five year term premium from Adrian, Crump and Moench (2013).

2.4 The Bond Risk Premium

The bond risk premium, also called the term premium, is the difference between long-term bond yield and the average of the expected future short-term nominal interest rates. Formally, I define the bond risk premium in equation (2). It measures the degree to which the long-term debt is more expensive than short-term debt. A variant of the BRP, which some papers use, is the next period expected return of a long-term bond in excess of that of a one period riskless bond. Mathematically, as in equation (3), the regular bond term premium is mechanically equal to the average of all future holding period excess returns.

$$y_t(n) = \underbrace{\frac{1}{n}\sum_{i=0}^{n-1} E_t y_{t+i}(1)}_{\text{Sum of Expected Short Rates}} + \underbrace{x_t(n)}_{\text{Term Premium}} \tag{2}$$

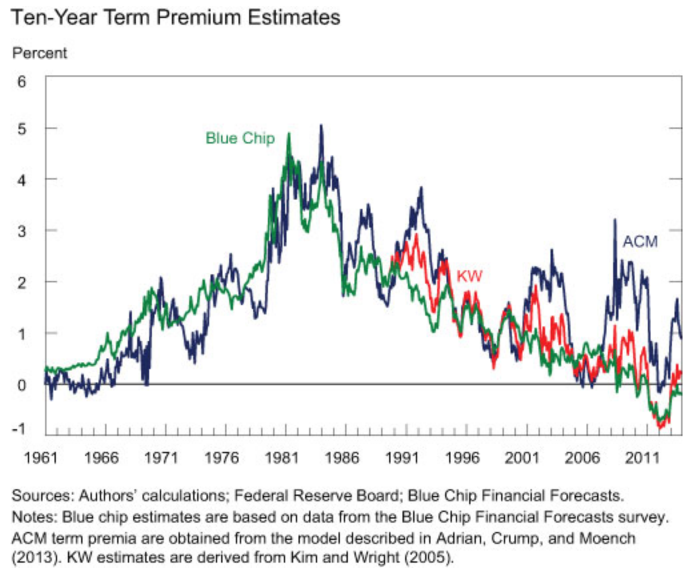
$$x_t\left(n\right)=\frac{1}{n}\sum_{i=0}^{n-1}E_t\left[p_{t+i+1}^{(n-i-1)}-p_{t+i}^{(n-i)}-y_{t+i}^{(1)}\right] \qquad (3)$$
$$=\frac{1}{n}\sum_{i=0}^{n-1}E_t\left[rx_{t+i}^{n-i+1}\right].$$

In the baseline regression, I focus on the regular measure of the bond term premium, because it is a direct measure for comparing the relative costs of borrowing across maturities. In addition, it also happens to be the measure that policymakers care about. However, in section 5 on robustness checks, I verify the results using the expected excess returns version of the BRP from Cochrane and Piazzesi (2005) and find that the results are very similar.

Since expectations of future short-term interest rates are not observable, the term premium must be constructed from either statistical or survey-based measures of short rate expectations. In the baseline regression, I use the term premiums derived by Adrian, Crump and Moench (2013) (ACM) at the New York Fed. The authors estimate an exponentially affine term structure model of interests on directly observed market coupon bond prices. It is a popular measure that is recognized by many policymakers and market participants as credible and having good out of sample properties.[11] Furthermore, in order to address the concern that my results are uniquely dependent on the BRP measure used, I verify the results with three alternative measures for BRP: 1) the slope of the yield curve; 2) the Cochrane-Piazzesi excess returns measure; and 3) the Kim-Wright survey-based measure. The slope of the yield curve is a nonparametric measure that has been documented to predict excess returns especially in the short run. The Cochrane-Piazzesi measure is the predicted excess returns measure of the BRP. The Kim-Wright measure is special because it is estimated using both the yield curves and survey data.

[11] A number of authors (Bernanke (2015)) agree that especially in the post financial crisis period, the realized short term nominal rates, which have been low relative to long term rates from adjacent prior years, confirm the high term premium predicted by the ACM model.

Figure 4: Comparison of the ACM Term Premium With Alternatives

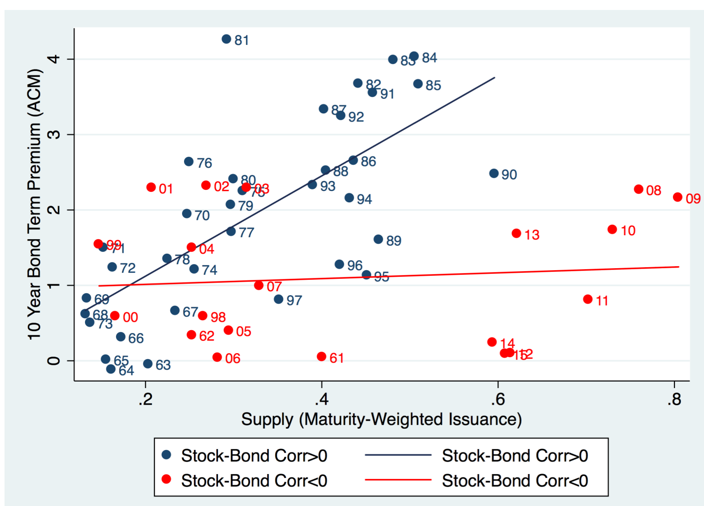


3 Empirical Results

3.1 Baseline Result

3.1.1 Supply Effect Increases in the Stock-Bond Correlation

Figure 5: Plot of Bond Risk Premium vs. Supply by the Sign of the Stock-Bond Correlation



In this section, I examine the response of the bond risk premium to new Treasury issuances between 1961 and 2016. I regress the bond risk premium on the maturity-weighted issuance measure of Treasury supply (MWI) while controlling for the correlation of the stock and bond returns and I find that the supply effect on BRP increases with the stock-bond correlation. The results are presented in Table (1). The 10 year maturity choice is merely serving as a representative maturity. As shown below, both empirically and theoretically, the estimates on all the maturities are qualitatively similar and in fact are amplified across maturities. The bond risk premium is in percentages and the *MWI* measure is in decimals and defined as above. The *stock-bond correlation* is calculated using the DCC (GARCH(1,1)) model, described in the previous section. The *1-year yield* is the Treasury 1-year constant maturity bond yield. Finally, *sign* is a dummy variable that takes the value of one when the stock-bond correlation is positive. Because it is an overlapping monthly regression, there is induced serial correlation. Newey-West standard errors with 48 lags are reported in the tables.

The results in column (1) of Table 1 indicate that unconditionally there is a positive relation between supply and BRP. Recall that a one unit increase in *MWI* means that issuing a maturity-weighted Treasury is equal to the size of the nominal GDP. A one unit increase in the maturity-weighted supply raised the required BRP by 1.8%, which is not statistically significant. In the regression for columns (2) and (3), I control for the stock-bond correlation. The results in these two columns show that the positive relation between BRP and supply (*MWI* coefficient) becomes both stronger and statistically significant. A one unit increase in supply raises the BRP by about 4%. There is a noticeable jump in R^2 value from column (1) to columns (2) and (3). The *MWI* supply is not readily interpretable. A back of the envelope estimation implies that the combined Treasury purchase of QE 1 and 2 ($900 billion), would have lowered the 10-year bond risk premium by about 60bps. This compares with the estimates by D'Amico and King (2013) and Li and Wei (2013), who estimate the impact as lowering 10 year yields by about 90 bps. The key variable of interest is the interaction term between supply and the stock-bond correlation. In columns (3)-(5), the coefficient on *MWI x Corr* is positive and statistically significant in each case, which indicates that the supply effect increases with the stock-bond correlation. Columns (4) and (5) show that the effect is robust to the inclusion of the nominal one year interest rate and the sign of the correlation. I control for the one-year rate or the short rate, because the BRP is known to be positively correlated with the level of the short rate. I also control for the sign of the correlation because the correlation changed signs quite abruptly. Controlling for the sign helps address the concern that the effect might be purely driven by a switch in economic regimes in the late 1990s.

Figure 5 provides an easy way to visualize and understand the empirical findings. Here I have divided the observations into two groups: the instances in which the stock-bond correlation is positive and the instances in which it is negative. In each case, I plot the 10-year bond risk premium against the MWI supply measure. The two fitted lines with distinctly different slopes can be interpreted as demand curves for Treasury bonds. When the stock-bond correlation is positive, the demand curve is steep, suggesting that the bond risk premium is very responsive to supply; when stock-bond correlation is negative, the demand curve, is nearly flat, suggesting that the bond risk premium is very unresponsive to supply changes. The latter case corresponds to the experience since the 2008 financial crisis that the removal of large quantities of long-term debt from the market due to QE has only led to a very modest reduction in the term premium.[12]

Table 1: THE TIME-VARYING TREASURY SUPPLY EFFECT AND THE STOCK-BOND CORRELATION: BASELINE SPECIFICATION

Variables	(1) TP10	(2) TP10	(3) TP10	(4) TP10	(5) TP10
MWI	1.791	3.395***	4.036***	4.185***	4.024***
	(1.126)	(0.922)	(0.763)	(0.709)	(0.736)
Corr		2.485***	-0.382	-1.211	0.156
		(0.659)	(1.351)	(1.446)	(1.597)
$MWI \times Corr$			**6.534*****	**5.720****	**6.203****
			(2.509)	(2.645)	(2.510)
1Y Yield				0.143**	
				(0.058)	
Sign					-0.271
					(0.508)
Constant	1.004***	0.294	0.214	-0.551	0.364
	(0.380)	(0.434)	(0.343)	(0.503)	(0.396)
Observations	665	665	665	665	665
Adjusted R-squared	0.07	0.41	0.48	0.55	0.48

*** $p<.01$, ** $p<.05$, * $p<.1$

Notes: Newey-West standard errors (48 lags) are shown in the parentheses. *TP10* is the 10-year statistical term premium from Adrian, Crump and Moench (2013); *MWI* is the ratio between the maturity-weighted issuance and the nominal GDP; *Stock-Bond Corr* is the dynamic conditional correlation of the monthly returns of the S&P 500 Index and the 10-year Treasury bond index; *1Y Yield* is the Treasury constant maturity 1 year nominal yield; *Sign* is a dummy variable that equals to 1 when the stock-bond correlation is positive.

[12] Hamilton and Wu (2012) estimates that retiring $ 400 billion of long term Treasuries would have only reduced 10 year yield by 14 basis points.

One concern about the *MWI* as the measure of supply is that debt issuance or the deficit is countercyclical. A latent business cycle factor could be driving both the bond risk premium and the amount of debt issuance. I regress the bond risk premium onto the weighted maturity of issuance and issuance quantity separately. The *Iss/GDP* variable, which is the ratio of the total face value of debt issuance over 12 months to GDP, measures directly the quantity of debt issuance normalized by GDP. By controlling for quantity, it partly addresses the endogeneity issue and partly shows the "supply" effect due to maturity structure changes. In Table (2), both the quantity and *WAM x Corr* coefficients are positive and significant. *WAM* by itself is positive but not significant. *Iss/GDP* does not drive out the cross-partial effects. This demonstrates that it is not simply that the quantity of debt that influences BRP but that maturity structure itself actually matters. Further, the effect continues to be robust to the inclusion of the short rate and the sign of the correlation.

Table 2: The Time-varying Treasury Supply Effect and the Stock-Bond Correlation: Controlling for Issuance Quantity

Variables	(1) TP10	(2) TP10	(3) TP10	(4) TP10	(5) TP10
WAM	0.330	0.282	0.313	0.188	0.299
	(0.405)	(0.272)	(0.219)	(0.184)	(0.222)
Corr		2.583***	-1.695	-2.162	-1.004
		(0.559)	(1.531)	(1.730)	(1.822)
WAM × *Corr*			**1.590***	**1.272**	**1.492***
			(0.512)	(0.559)	(0.510)
Iss/Quant	4.514	15.611***	15.471***	20.494***	15.957***
	(6.302)	(4.330)	(3.817)	(3.669)	(4.000)
1Y Yield				0.170***	
				(0.052)	
Sign					-0.289
					(0.605)
Constant	0.211	-1.497**	-1.429***	-2.752***	-1.315**
	(0.646)	(0.619)	(0.499)	(0.677)	(0.523)
Observations	665	665	665	665	665
Adjusted R-squared	0.08	0.44	0.52	0.60	0.52

*** p<.01, ** p<.05, * p<.1

Notes: Newey-West standard errors (48 lags) are shown in the parentheses. *TP10* is the 10-year statistical term premium from Adrian, Crump and Moench (2013); *WAM* is the weighted average maturity of issuance over the following 12 months; *Corr* is the dynamic conditional correlation of the monthly returns of the S&P 500 Index and the 10-year Treasury bond index; *Iss/Quant* is the ratio between the total quantity of Treasury issuance and the nominal GDP; *1Y Yield* is the Treasury constant maturity 1 year nominal yield; *Sign* is a dummy variable that equals to 1 when the stock-bond correlation is positive.

3.1.2 Instrumental Variable Test

To further address the concern that the supply measure may be endogenous, I use the WAM of issuance as an instrument. As discussed previously, the supply measure may be endogenous because it is mechanically driven by the issuance (or roughly deficit) to GDP ratio, which may be countercyclical. On the other hand, there is evidence that the WAM of the issuance is relatively insensitive to the relative costs of borrowing but has historically been driven primarily by the objective of the stabilizing the Treasury's portfolio. I discuss the evidence for the validity of the WAM of issuance as an instrument in greater detail in Section 2.

The results are presented in Table (3). The top panel shows the results from the first stage regression. R^2 is close to 90%, which confirms that most of the variations in the maturity-weighted supply measure comes from the maturity choice of issuance. The main results are shown in the second panel. The results are broadly very similar. The coefficient on the supply measure is again positive but only significant from column (2)- (4). However, they are somewhat smaller compared to the baseline results. The more important variable of interest is the interaction term "$\hat{\text{MWI}} \times$ Corr is positive and significant and the magnitude is also comparable to those in the baseline regression.

3.1.3 Summary

The results show that the sensitivity of the bond risk premium to new Treasury supply is systematically time-varying. In particular, the bond risk premium increases more per unit of supply as the stock-bond correlation increases. The theoretical intuition given so far for the empirical results is that in an asset market of limited arbitrage, arbitrageurs demand an additional risk premium for absorbing a new supply of Treasury bonds. As bonds become better hedges for stocks held by the arbitrageurs, the compensatory bond risk premium is reduced by the amount of the hedging benefits of the bonds.

4 Theoretical Framework

In this section, I use a modified version of the preferred habitat model explain the empirical results presented in section 3. There are two types of agents. The first type is the preferred

Table 3: THE TIME-VARYING TREASURY SUPPLY EFFECT AND THE STOCK-BOND CORRELATION: WAM OF ISSUANCE AS THE INSTRUMENT

Panel A

First Stage Regression: $\text{MWI}_t = \alpha + \beta \cdot \text{WAMiss}_t + \delta y_t^{(1)} + u_t$

	Instrument = WAMiss_t
WAMiss	.210
	(.003)
1Y Yield	-.010
	(.001)
R^2	0.90

Panel B

Second Stage Regression: $\text{TP}_t = \alpha + \beta \cdot \hat{\text{MWI}}_t + \gamma \cdot \hat{\text{MWI}} \times \text{Corr} + \delta' X_t + u_t$

Variables	(1) TP10	(2) TP10	(3) TP10	(4) TP10
$\hat{MWI}$	1.223	3.182***	3.458***	3.176***
	(1.335)	(0.903)	(0.849)	(0.888)
Corr		-0.383	-1.426	-0.224
		(1.458)	(1.510)	(1.830)
$\hat{MWI}$ x Corr		**6.114****	**5.664****	**6.001****
		(2.788)	(2.864)	(2.892)
1Y Yield			0.151**	
			(0.070)	
Sign				-0.076
				(0.544)
Constant	1.207**	0.518	-0.324	0.561
	(0.470)	(0.390)	(0.562)	(0.418)
Observations	666	666	666	666
Adjusted R-squared	0.03	0.39	0.46	0.39

*** p<.01, ** p<.05, * p<.1

Notes: Newey-West standard errors (48 lags) are shown in the parentheses. *TP10* is the 10-year statistical term premium from Adrian, Crump and Moench (2013); *WAMiss* is the weighted average maturity of issuance over the following 12 months; *Corr* is the dynamic conditional correlation of the monthly returns of the S&P 500 Index and the 10-year Treasury bond index; *1Y Yield* is the Treasury constant maturity 1 year nominal yield; *Sign* is a dummy variable that equals to 1 when the stock-bond correlation is positive.

habitat (PH) borrowers or debt issuers, who are relatively price-inelastic and supply a continuum (of maturities) of Treasury bonds. I consider the U.S. Treasury (net of the Federal Reserve's demands) as a PH borrower. This assumption is valid if the Treasury's issuance policy, in terms of how much it issues in any particular maturity, is relative insensitively to the relative bond prices.[13] In the absence of any other types of traders, the PH investors's supply schedule could cause bonds of nearby maturities (in other words close substitutes) to have

[13]This assumption is justified by the discussion in Section 2. In Hou (2017), I provide evidence that the maturity choice of the Treasury issuance is almost entirely due a desire to stabilize the maturity structure of the total Treasury debt portfolio and the debt to GDP ratio. This finding is also consistent with the Treasury's own stated objective that it does not engage in tactical issuance or market timing (Garbade (2007)).

wildly different prices. The second type of agents is the risk-averse arbitrageurs/investors (Arb) who integrate the bond markets by absorbing supply shocks in exchange for risk premiums. They are the net demanders of bonds in this model. Arbitrageurs can invest in a continuum of nominal bonds and a single stock index. I do not allow multiple stocks because the focus of the paper is on bonds and a single stock index is sufficient to illustrate the intuition of the paper. Furthermore, Lines (2016) documents that the portfolio of most large investment funds are benchmarked to the S&P 500 Index. Finally, in line with Brennan and Xia (2002), I assume an exogenous stock price process with a constant equity risk premium. In the Appendix, I show that it is possible to allow a stock price process with a time-varying equity premium, as predicted by the short rate. The results are amplified when such a generalization is made.

Because the model though simple has quite a few pieces, it may be useful to provide a roadmap. First, I introduce the PH suppliers, who have exogenous price inelastic supply functions. Second, I describe the economic problem of the representative Arb, who is the marginal investor in all maturities of bonds. Third, I describe the exogenous short rate and stock price processes. I conjecture that the bond price has a standard exponentially affine form and derive expressions for bond returns. Fourth, I plug in the expressions for bond returns and stock returns into the Arb's budget constraint, verify the bond price functional forms and obtain as the Arb's first order conditions that the bond risk premium is a linear function of the risk factors. Finally, I use asset market clearing (Arb demand equals PH supply) to generate an equilibrium relation between the bond risk premium and the supply quantities with which I generate comparative statics predictions.

4.1 Preferred Habitat (Treasury) Supply Policy

Following Greenwood and Vayanos (2014), I assume that the Treasury supply of bonds (net of Federal Reserve and other intergovernmental holdings) is driven by a single factor model. The dollar value of the maturity τ bond supplied to the Arbs is:

$$s_t^{(\tau)} = \zeta_t\left(\tau\right) + \theta\left(\tau\right)\beta_t \tag{4}$$

where $s_t^{(\tau)}$ is the dollar amount of the bond issued in maturity τ. $\zeta(\tau)$ is the average supply of maturity τ. β_t is a stochastic aggregate supply factor and may be thought of as new budget deficits that must be financed. $\theta(\tau)$ measures the sensitivity of the individual bond supply to the aggregate supply shock. β_t follows an Ornstein-Uhlenbeck process, which is essentially the continuous analogue of an AR(1) process:

$$d\beta_t = -\kappa_\beta \beta_t dt + \sigma_\beta dB_{\beta,t} \tag{5}$$

4.2 Arbitrageurs's Objective

The Arbs invest in a stock index and a continuum (indexed by maturity) of nominal bonds. Arbs essentially act as "banks" and other large financial institutions that participate actively in the bond market. It is well-known that a group known as the "primary dealers," who are typically the largest financial institutions, act essentially as "wholesalers" in the primary Treasury (auction) markets.[14] The Arbs maximize the mean-variance of the expected instanenous increase in wealth of their portfolio. The objective may be motivated by a value-at-risk internal regulatory constraint within a risk-neutral institution. Formally, the Arbs's objective function is defined as:

$$\max_{\left\{x_t^{(\tau)}\right\}} \left[E_t\left(dW_t\right) - \frac{a}{2}Var_t\left(dW_t\right)\right]. \tag{6}$$

a is the risk-aversion parameter. The Arbs are subject to the following budget constraint:

$$dW_t = \underbrace{\int_0^T x_t^{(s)} \frac{dP_t^{(s)}}{P_t^{(s)}}}_{\text{Stock Return}} + \underbrace{\int_0^T x_t^{(\tau)} \frac{dP_t^{(\tau)}}{P_t^{(\tau)}} d\tau}_{\text{Bond Portfolio Returns}} + \underbrace{\left(W_t - \int_0^T x_t^{(\tau)} d\tau\right) r_t dt}_{\text{Riskfree Rate Return}}. \tag{7}$$

where $x_t^{(\tau)}$ is the dollar investment in the bond of maturity τ and $x_t^{(s)}$ is the dollar investment in the stock index. The Arbs have a short horizon objective, where they maximize the returns to wealth from period to period. The model can be thought of as being the steady state of an overlapping generations model.

[14] In a new strand of literature "intermediary asset pricing," He, Kelly and Manela (2017) test the theory proposed by He and Krishnamurthy (2013). They show that a stochastic discount factor constructed based on the equity capital ratio of the primary dealers has significant explanatory power for the cross-sectional expected returns of a host of asset classes.

4.3 Equilibrium Bond Prices and Bond Returns

In addition to the Treasury supply policy, I assume two additional exogenous asset return processes. First, the nominal short rate follows an exogenous Ornstein-Uhlenbeck process:

$$dr_t = \kappa_r (\bar{r} - r_t) dt + \sigma_r dB_{r,t}. \tag{8}$$

where κ_r is the sensitivity of the mean-reversion of the interest rate process. σ_r represents the volatility of the short rate. The short rate may be thought of as being determined by the Federal Reserve monetary policy. Secondly, I assume that the stock price follows a geometric Brownian motion:

$$ds_t = \frac{dP_t^s}{P_t^s} = (r_t + \sigma_s \xi_s) dt + \sigma_s dB_{s,t}. \tag{9}$$

where σ_s represents the volatility of the stock price. ξ_s represents a constant unit equity risk premium associated with the stock return innovation, dB_s.[15]

The bond prices and hence bond returns are recursively determined in equilibrium as solutions to stochastic differential equations. I solve the the model using a guess-and-verify method. I conjecture that the price of a zero coupon bond of maturity τ is exponentially affine so that the bond yields are linear in the risk factors r_t, β_t, and s_t.[16] The price of the maturity τ zero coupon bond can written as:

$$P_t^{(\tau)} = \exp\left[-\left(A_r(\tau) r_t + A_\beta(\tau) \beta_t + A_s(\tau) s_t + C(\tau)\right)\right]. \tag{10}$$

where $A_r(\tau)$, $A_\beta(\tau)$ and $A_s(\tau)$ measure the sensitivity of the bond price to the risk factors. The $A_i(\tau)$'s and $C(\tau)$ are solutions to the ordinary differential equations implied by the asset market clearing conditions below. I can now express the instantaneous bond return, $dP_t^{(\tau)}/P_t^{(\tau)}$, in terms of the underlying shocks. By applying Îto's lemma to equations (5)-(10), I obtain the following expression:

$$\frac{dP_t^{(\tau)}}{P_t^{(\tau)}} = \mu_t^{(\tau)} dt - A_r(\tau) \sigma_r dB_{r,t} - A_\beta(\tau) \sigma_\beta dB_{\beta,t} - A_s(\tau) \sigma_s dB_{s,t}. \tag{11}$$

[15] The expected stock return is equal to $r_t + \sigma_s \xi_s$. The difference between the expected stock return and the short rate r_t is therefore the equity risk premium, $\sigma_s \xi_s$.

[16] The zero coupon bond price and bond yield are related in the following way: $y_t^{(\tau)} = -\frac{\log P_t^{(\tau)}}{\tau}$.

where μ_t^τ denotes the following complicated expression:

$$\begin{aligned}\mu_t^{(\tau)} =& A_r^{'}(\tau)\, r_t + A_\beta^{'}(\tau)\,\beta_t + A_s^{'}(\tau)\, s_t + C^{'}(\tau) \\ & - A_r(\tau)\,\kappa_r(\bar{r} - r_t) + A_\beta(\tau)\,\kappa_\beta \beta_t - A_s(\tau)(\bar{r} + \sigma_S \xi_t) \\ & + \frac{1}{2} A_r(\tau)^2 \sigma_r^2 + \frac{1}{2} A_\beta(\tau)^2 \sigma_\beta^2 + \frac{1}{2} A_s(\tau)^2 \sigma_s^2 .\end{aligned} \tag{12}$$

μ_t^τ is the expected instantaneous return. In the Appendix, I verify the bond price by solving for $A_r(\tau)$, $A_\beta(\tau)$, $A_s(\tau)$ and $C(\tau)$ as deterministic functions of τ. In particular, I show that $A_s(\tau) = 0$.

4.3.1 Correlation between Stock and Nominal Bond Returns

The stock and bond return correlation can now be calculated. I make two simplifying assumptions: $cov(dB_r, dB_s) = \sigma_{\beta r} = 0$ and $cov(dB_\beta, dB_s) = \sigma_{\beta s} = 0$. These assumptions are not necessary, however they are very useful for deriving easily interpretable closed form solutions. The first assumption says that the bond supply shock and the interest rate shocks are uncorrelated. I show in the Appendix that similar to Greenwood and Vayanos (2014), relaxing this assumption, which significantly complicates the algebra, does not affect the results qualitatively. The second assumption says that the bond supply shock and the stock return shocks are uncorrelated. It is a less innocent assumption. There is reason to believe a sharply adverse stock return, say a financial crisis or the news of an impending recession, may be predictive of future deficits. However, at the frequency (less or equal to a year) that I examine it is not unreasonable to think that deficits may respond less quickly than stock returns.

Under these assumptions, the stock-bond return correlation may be calculated as below:

$$\rho_{bs} = Corr\left(\frac{dP_t^{(\tau)}}{P_t^{(\tau)}}, \frac{dP_t^{(s)}}{P_t^{(s)}}\right) \tag{13}$$

$$\begin{aligned} &= Corr\left(-A_r(\tau)\,\sigma_r dB_{r,t} - A_\beta(\tau)\,\sigma_\beta dB_{\beta,t} - A_s(\tau)\,\sigma_s dB_{s,t},\ (r_t + \sigma_S \lambda_S)\, dt + \sigma_s dB_{s,t}\right) \\ &= Corr\left(-A_r(\tau)\,\sigma_r dB_{r,t}, \sigma_s dB_{s,t}\right) \\ &= -\rho_{rs}. \end{aligned} \tag{14}$$

In other words, the stock-bond return correlation is exactly equal to the negative of the correlation between stock returns and the short rate. As a result, the stock-bond correlation is constant across the maturities. Moreover, the interest rate risk is the only shock that matters.

4.4 Arbitrageurs's Demand

I solve for the arbitrageurs' demand by plugging expressions for the bond returns in equation (11) and stock return in equation (9) into the budget constraint (7) and in turn plugging the budget constraint into the objective function. Once again, I use the simplifying assumptions that $Cov(\beta_t, r_t) = Cov(\beta_t, s_t) = 0$. The Arb's objective function can then be rewritten as follows:

$$
\begin{aligned}
\max_{\left\{x_t^{(\tau)}\right\}} & \left(\left[\int_0^T x_t^{(\tau)}\left(\mu_t^{(\tau)} - r_t\right) d\tau + x_t^{(s)} \sigma_S \xi_S\right]\right) dt \\
& - \sum_{i=r,\beta,s} \frac{a\sigma_i^2}{2}\left(\int_0^T x_t^{(\tau)} A_i(\tau)\, d\tau\right)^2 - \frac{a\sigma_s^2}{2}\left(x_t^{(s)}\right)^2 \\
& + a\left(\int_0^T x_t^{(\tau)} A_r(\tau)\, d\tau\right) x_t^{(s)} \sigma_r \sigma_s \rho_{r,s} + a\left(\int_0^T x_t^{(\tau)} A_r(\tau)\, d\tau\right) x_t^{(s)} \sigma_s^2 \\
& + a\left(\int_0^T x_t^{(\tau)} A_r(\tau)\, d\tau\right)\left(\int_0^T x_t^{(\tau)} A_s(\tau)\, d\tau\right) \sigma_s \sigma_r \rho_{r,s} + (\text{Constant Terms}).
\end{aligned}
\tag{15}
$$

By maximizing the mean-variance objective with respect to the budget constraint, I obtain the Arbs' optimal demand for the Treasury bond each maturity τ. The first order conditions can be written as characterizations of the instantaneous excess returns:

$$
\begin{aligned}
\mu_t^{(\tau)} - r_t =& A_r(\tau)\lambda_{r,t} + A_\beta(\tau)\lambda_{\beta,t} + A_s(\tau)\lambda_{s,t} \\
& - A_r(\tau)\lambda_{r,t} x_t^{(s)} \frac{\sigma_s^2}{\sigma_r^2} - \left(A_s(\tau) + A_r(\tau)\left(1 + x_t^{(s)}\right)\right)\lambda_{r,t}\frac{\sigma_s}{\sigma_r}\rho_{r,s}.
\end{aligned}
\tag{16}
$$

where

$$
\lambda_{i,t} = a\sigma_i^2 \int_0^T x_t^{\tau} A_i(\tau)\, d\tau,\ \ i \in \{r, \beta, s\} \tag{17}
$$

and $\lambda_{i,t}$ denotes the price of risk for risk factor i. For example, $\lambda_{r,t}$ represents the price of the interest rate risk.

4.5 Asset Market Clearing

In equilibrium, the stock and bond markets clear, so the following conditions hold:

$$\begin{aligned} x_t^{(\tau)} &= s_t^{(\tau)} = \zeta_t^{(\tau)} + \theta\left(\tau\right)\beta_t \\ x_t^{(s)} &= \bar{x}_t^{(s)} \end{aligned} \tag{18}$$

The second equality is the assumption that the Arbs's stockholding is exogenous and fixed. Essentially, I am requiring that the Arbs cannot finance the purchase of the new bonds by selling down the stocks they hold. In other words, they cannot move investment capital across asset classes and must finance bond purchase with either cash or the risk-free bonds. I make this assumption so that the equilibrium characterization of the bond risk premium has an easily interpretable functional form. Yet, this assumption is also justified by market realism. Many institutional bond traders, such as the trading desks at investment banks or hedge funds, are typically part of a business that is essentially exposed to the stock market risk (which in turn proxies business cycle risk). They cannot easily shed substantial exposure to the stock market without essentially exiting their business. This assumption is also consistent with looking at the effect of supply upon the impact of the supply shock or in the very short run. Finally and fortunately, this assumption is not necessary for the results to go through qualitatively. More generally, I only need that the Arb investors face a downward-sloping demand curve for stocks, so that it is slow to unload them when the return correlation turns adverse.

The asset market equilibrium implies a set of ordinary differential equations (ODEs) that allows me to solve for $A_r(\tau)$, $A_\beta(\tau)$ and $A_s(\tau)$ as deterministic functions of τ. The details are in the Appendix. In particular, I find that $A_s(\tau) \equiv 0$. In other words, bond prices are not sensitive to the dynamics of stock returns except through the correlation between stock returns and the short rate. This also significantly simplifies the expression for the bond risk premium into the following form:

$$\mu_t^{(\tau)} - r_t = \underbrace{A_r(\tau)\lambda_{r,t}}_{\text{Interest Rate Risk}} + \underbrace{A_\beta(\tau)\lambda_{\beta,t}}_{\text{Supply Risk}} + \underbrace{A_r(\tau)\lambda_{s,t}\frac{\sigma_s}{\sigma_r}\rho_{b,s}\bar{x}_t^{(s)}}_{\text{Correlational Risk}} \tag{19}$$

where:

$$\lambda_{i,t} = a\sigma_i^2 \int_0^T \left(\zeta_t^{(\tau)} + \theta(\tau)\beta_t\right) A_i(\tau)\, d\tau.$$

Note that the bond risk premium now has three easily interpretable components. The first two terms are the same as in Greenwood and Vayanos (2014). They are the interest rate risk premium and supply risk premium, respectively. Both effects are driven by the fact that long-term bonds suffer capital loss from an unexpected short rate increases. The interest rate premium is a compensation on the intensive margin for a given bond portfolio. The supply risk premium compensates the investors on the extensive margin for the new bonds purchased.

The third term and also the new addition in this paper is the covariance risk term. It is the additional bond risk premium component that is induced by the hedging properties of the nominal bonds. It says that the required risk premium depends on the amount of hedging value the bonds can provide for the stocks held by the Arb investors. Intuitively, this term is proportional to the risk aversion of the Arbs, the volatility of stocks and bonds, the quantity of the stocks held and the correlation of stock and bond returns. Note that this term does not have to be positive depending on the sign of the stock-bond correlation. In particular, when the stock-bond correlation turns sufficient negative, it is possible for the third term to pull the overall bond risk premium towards zero, something that seems to have happened in the last decade.

New Treasury supply, which is represented by β, affects the bond risk premiums through the prices of risk λ_i's. The prices of risk λ is essentially a maturity-weighted sum of exposure to risk factors. They are somewhat similar to the calculation of a bond duration term. The purchase of new bonds increases the amount of the investors's exposure to the risk factors. The longer the maturity of the bonds the more generally more sensitive is the exposure.

4.6 Comparative Statics Predictions

With the characterization of the equilibrium bond risk premium in equation (19), I am now able to make some theoretical predictions. Prediction 1 generalizes the finding by Greenwood and Vayanos (2014) that supply raises bond risk premiums. Prediction 2 validates and hence rationalizes the empirical results that I have already presented in section 3 that the supply effect is systematically time-varying. Prediction 3 is a corollary and a new implication of the model that the sensitivity of the supply effect increases across the maturities.

Prediction 1: The Treasury supply effect on the bond risk premium is positive if $\rho_{r,s}$ is sufficiently nonnegative.

I characterize the level of the supply effect by taking a derivative of the equilibrium bond risk premium (equation 19) with respect to β_t or the quantity of debt. The supply effect is shown in the following expression

$$\begin{aligned}\frac{\partial\left(\mu_t^{(\tau)}-r_t\right)}{\partial\beta_t} =& a\left(\sigma_r^2+\sigma_r\sigma_s\rho_{b,s}\bar{x}_t^{(s)}\right)A_r\left(\tau\right)\int_0^T A_r\left(\tau\right)\theta\left(\tau\right)d\tau \\ &+a\sigma_\beta^2 A_\beta\left(\tau\right)\int_0^T A_\beta\left(\tau\right)\theta\left(\tau\right)d\tau.\end{aligned} \tag{20}$$

Because $A_r(\tau)$ and $A_\beta(\tau)$ are both positive functions of τ, the supply effect is positive as long as ρ_{bs} is not too negative. The ρ_{bs} is bounded from below by -1. So in theory, even if $\rho_b s \equiv -1$, the supply effect does not have to be negative. However, in the data (see Figure 5), the slope of demand curve has a slope close to zero when the stock-bond correlation is negative. This means that the contribution of the supply from the covariance risk term must have been sufficiently negative so that the overall bond risk premium is largely unresponsive to supply shocks.

Prediction 2: The supply effect increases with the stock-bond correlation.

This prediction verifies the main empirical finding of the paper. I derive the sensitivity of the supply effect by differentiating equation (20) with respect to ρ_{bs}.

$$\frac{\partial^2\left(\mu_t^{(\tau)}-r_t\right)}{\partial\beta_t\partial\rho_{b,s}}=a\sigma_r\sigma_s\bar{x}_t^{(s)}A_r\left(\tau\right)\int_0^T A_r\left(u\right)\theta\left(u\right)du>0 \tag{21}$$

Evidently, the cross-partial derivative is positive, which indicates that the supply effect is increasing in the stock-bond correlation. This result theoretically verifies and rationalizes the empirical findings reported in Table 1. In the presence of a positive amount of stockholding, the absorption of additional supply, which manifests in additional duration risk/interest rate risk, must be compensated by a higher bond risk premium. This effect is increasing in the Arb investor's risk aversion, the interest rate or stock return volatility and finally in the amount of stocks held by Arbs.

Prediction 3: The supply effect's sensitivity to the stock-bond correlation increases with maturity

The last prediction of the model is that the sensitivity of the Treasury supply effect (to the stock-bond correlation) is in fact higher for bond risk premiums at longer maturity horizons. I show this theoretically by differentiating equation 21 with respect to τ.

$$\frac{\partial}{\partial\tau}\left(\frac{\partial^2\left(\mu_t^{(\tau)}-r_t\right)}{\partial\beta_t\partial\rho_{bs}}\right)=\underbrace{A_r^{'}\left(\tau\right)}_{>0}\cdot\underbrace{a\sigma_r\sigma_s\bar{x}_t^{(s)}\int_0^T A_r\left(u\right)\theta\left(u\right)du}_{>0}>0$$

This result has not yet been empirically tested and it is what I will proceed to do. I test that prediction by regressing bond risk premiums of incremental maturities on the supply measure and the stock-bond correlation. The results are presented in Table 4. The $MWI\times Corr$ coefficients increase from 5.5 at 2 years to about 9.8 at 10 years. The intuition for the result is that long term bonds are more sensitive to short rate risk. Because of the simple assumptions, the model almost mechanically generates a monotonic trend in the supply effect if the interest rate (duration) risk is the sole risk affecting the term structure of the BRP. The fact that the empirical evidence confirms this prediction also provides indirect corroborating evidence for the assumption about the short rate risk being the primary risk.

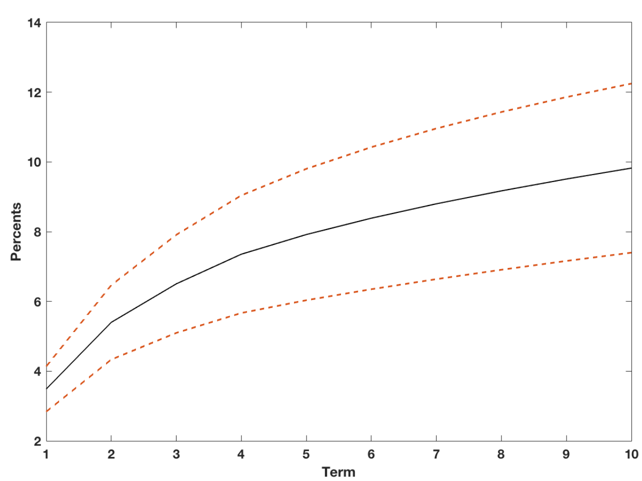
Table 4: The Sensitivity of Supply Effect Increases with the Maturity

Variables	(1) TP02	(2) TP03	(3) TP04	(4) TP05	(5) TP10
MWI	1.757***	2.256***	2.654***	2.985***	4.042***
	(0.312)	(0.398)	(0.465)	(0.517)	(0.681)
$Corr$	-0.818	-1.000	-1.116	-1.199	-1.387
	(0.548)	(0.728)	(0.869)	(0.980)	(1.292)
$MWI \times Corr$	**5.480***	**6.610***	**7.354***	**7.918***	**9.823***
	(1.084)	(1.425)	(1.686)	(1.884)	(2.424)
Constant	-0.042	-0.008	0.030	0.069	0.273
	(0.140)	(0.178)	(0.210)	(0.237)	(0.323)
Observations	665	665	665	665	665
Adjusted R-squared	0.53	0.53	0.52	0.51	0.50

*** p<0.01, ** p<0.05, * p<0.1

Notes. Newey-West HAC standard errors in parentheses. $TP`n'$ is the ACM n year term premium; MWI is the maturity-weighted issuance to nominal GDP ratio; $Corr$ is the dynamic conditional correlation of month returns of the S&P 500 Index and the 10-year Treasury bond index; $MWI \times Corr$ is the interaction term between MWI and $Corr$.

Figure 6: MWI Interaction Coefficients at Different Maturities

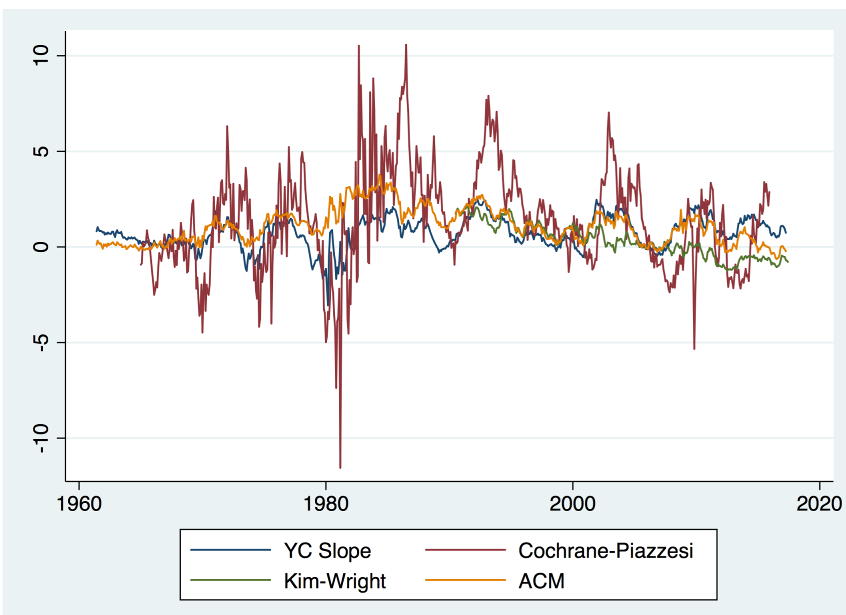


5 Robustness Checks

5.1 Alternative Measures of Ex Ante BRP

This section addresses the concern that the results may be dependent on the particular choice of ACM risk premium estimates. Adrian, Crump and Moench (2013) extract the bond term premia from a purely statistical no-arbitrage bond pricing model. While it has become popular with industry practitioners and central bank policymakers alike, there is always the worry that these risk premium estimates could suffer from model misspecification. I try to address this concern by looking at three alternative measures of the ex ante BRP: (1) the slope of the yield curve; (2) the Cochrane and Piazzesi (2005) forward-rates-based BRP (CP); (3) the Kim and Wright (2005) survey-based BRP (KW). Figure 7 shows the time series plot of all four BRP measures. The ACM, YC and the KW measures of BRP follow each other pretty closely and CP measure is the most volatile. All these measures assume that the bond yields are the sum of expected future short term yield and BRP without forecast errors.[17]

Figure 7: Different Measures of Ex-ante BRP



[17]Cieslak (2016) shows that the bond investors exhibit extrapolative beliefs about interest rates, especially around turns of business cycles. People overestimate interest rates as the economy enters a recession and underestimates interest rates when it enters a boom. Allowing forecast errors is beyond the scope of this paper.

1. Term Spread

   The Term Spread (the steepness of the yield curve) is the simplest and a popular proxy for ex ante BRP. The shape of the yield curve reflects both the expectations of future short term interest rates and the required term (or risk) premium. Fama and Bliss (1987) and Campbell and Shiller (1991) show that in the near-term the yield curve predicts future excess bond returns rather than future yield changes. However, in the long term, the yield curve is a very poor predictor of BRP because of mean-reversion of short-rate expectations. In table 5, we show the results from regressing the difference between 3 and 1 year yields on the same set of regressors. We see that that a very similar pattern as the baseline regression with the ACM BRP. The "MWI x Corr" coefficients remain positive and statistically significant even though the statistical significance drops somewhat. In table 6, we see that the second prediction of the model continues to hold. The coefficients increase across the maturities. The statistical significance wanes as maturity increases. However, this could be consistent with the fact that at longer horizons, YC becomes a much poorer and noisier predictor of the BRP.

Table 5: The Time-varying Treasury Supply Effect and the Stock-Bond Correlation: Term Spread as BRP

Variables	(1) Slope3	(2) Slope3	(3) Slope3	(4) Slope3	(5) Slope3
MWI	1.016***	1.052***	1.312***	1.190***	1.313***
	(0.325)	(0.382)	(0.338)	(0.314)	(0.346)
$Corr$		0.063	-1.231	-0.737	-1.427
		(0.315)	(0.829)	(0.579)	(1.001)
$MWI \times Corr$			**3.206****	**4.647*****	**3.265***
			(1.604)	(1.237)	(1.668)
1Y Yield				-0.122***	
				(0.029)	
Sign					0.111
					(0.221)
Constant	0.058	0.042	0.010	0.674***	-0.052
	(0.147)	(0.169)	(0.151)	(0.206)	(0.232)
Observations	665	665	665	665	665
Adjusted R-squared	0.11	0.11	0.18	0.42	0.18

*** p<.01, ** p<.05, * p<.1

Notes: Newey-West standard errors (48 lags) are shown in the parentheses. *Slope*3 is the difference of 3 year and 1 year zero coupon yields;; MWI is the ratio between the maturity-weighted issuance and the nominal GDP; *Stock-Bond Corr* is the dynamic conditional correlation of the monthly returns of the S&P 500 Index and the 10-year Treasury bond index; *1Y Yield* is the Treasury constant maturity 1 year nominal yield; *Sign* is a dummy variable that equals to 1 when the stock-bond correlation is positive.

Table 6: The Sensitivity of Supply Effect Increases with the Maturity: Term Spread as BRP

VARIABLES	(1) Slope2	(2) Slope3	(3) Slope4	(4) Slope5	(5) Slope10
MWI	0.701***	1.312***	1.839***	2.289***	3.750***
	(0.197)	(0.338)	(0.438)	(0.513)	(0.720)
Stock-Bond Corr	-0.740	-1.231	-1.597	-1.888	-2.794
	(0.475)	(0.829)	(1.090)	(1.289)	(1.837)
MWI x Corr	**2.168****	**3.206****	**3.743***	**4.045***	**4.514**
	(0.937)	(1.604)	(2.081)	(2.435)	(3.407)
Constant	0.020	0.010	-0.008	-0.025	-0.063
	(0.086)	(0.151)	(0.201)	(0.238)	(0.342)
Observations	665	665	665	665	665
Adjusted R-squared	0.16	0.18	0.21	0.25	0.38

*** p<.01, ** p<.05, * p<.1

Notes. Newey-West HAC standard errors in parentheses. Slope-n is the difference of n year and 1 year zero coupon yields; ; MWI is the maturity-weighted issuance to nominal GDP ratio; $Corr$ is the dynamic conditional correlation of month returns of the S&P 500 Index and the 10-year Treasury bond index; $MWI \times Corr$ is the interaction term between MWI and $Corr$.

2. Cochrane-Piazzesi BRP

Cochrane and Piazzesi (2005) uncovered a better predictor of future bond returns than the yield curve. They regress realized bond returns on the five one-year forward rates (the one to five years ahead marginal discount rates in the term structure) and find that all bond returns seem to be predicted by a single forecasting factor. The single forecasting factor consists of a "tent-shaped" linear combination of forward rates. The CP-BRP is more volatile than the other measures because it is derived from realized excess returns. In table 7, we see that a very similar pattern as the baseline regression emerges. The "MWI" coefficients are bigger and become significant when the stock-bond correlation is controlled for. The "MWI x Corr" coefficients are positive and statistically significant. Finally, the R^2 jumps from merely to 2% to 20% when we control for stock-bond correlation. Once again, table 8 shows that the supply sensitivity to correlation increases with maturity. For the CP-BRP, we only go up to 5 years because the Fama-Bliss yields, which Cochrane-Piazzesi use, only go up to 5 years.

Table 7: The Time-varying Treasury Supply Effect and the Stock-Bond Correlation: Cochrane-Piazzesi BRP

	(1)	(2)	(3)	(4)	(5)
VARIABLES	CP-BRP-3y	CP-BRP-3y	CP-BRP-3y	CP-BRP-3y	CP-BRP-3y
MWI	1.204	2.035*	2.905***	2.506***	2.905***
	(1.105)	(1.123)	(0.843)	(0.755)	(0.817)
Stock-Bond Corr		1.464	-3.072*	-2.115	-3.057
		(0.988)	(1.806)	(1.456)	(2.201)
MWI x Corr			**11.240*****	**14.468*****	**11.238*****
			(3.625)	(3.000)	(3.535)
1Y Yield				-0.260***	
				(0.051)	
Sign					-0.009
					(0.621)
Constant	0.463	0.077	-0.017	1.486***	-0.012
	(0.395)	(0.494)	(0.356)	(0.485)	(0.524)
Observations	612	612	612	612	612
Adjusted R-squared	0.02	0.08	0.20	0.34	0.20

Newey-West HAC standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Notes: Newey-West standard errors (48 lags) are shown in the parentheses. CP-BRP-3y is the estimated ex-ante 3 year BRP. It is generated by regressing the realized excess returns of 3 year bonds on the Cochrane-Piazzesi factor, which is a linear combination of forward rates; *MWI* is the ratio between the maturity-weighted issuance and the nominal GDP; *Stock-Bond Corr* is the dynamic conditional correlation of the monthly returns of the S&P 500 Index and the 10-year Treasury bond index; *1Y Yield* is the Treasury constant maturity 1 year nominal yield; *Sign* is a dummy variable that equals to 1 when the stock-bond correlation is positive.

Table 8: The Sensitivity of Supply Effect Increases with the Maturity: Cochrane-Piazzesi BRP

VARIABLES	(1) CP-BRP-2y	(2) CP-BRP-3y	(3) CP-BRP-4y	(4) CP-BRP-5y
MWI	1.503***	2.905***	4.373***	5.181***
	(0.436)	(0.843)	(1.269)	(1.503)
Stock-Bond Corr	-1.590*	-3.072*	-4.624*	-5.479*
	(0.935)	(1.806)	(2.718)	(3.221)
MWI x Corr	**5.818*****	**11.240*****	**16.920*****	**20.049*****
	(1.876)	(3.625)	(5.456)	(6.465)
Constant	0.018	-0.017	-0.155	-0.291
	(0.184)	(0.356)	(0.535)	(0.634)
Observations	612	612	612	612
Adjusted R-squared	0.20	0.20	0.20	0.20

Newey-West HAC standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Notes. Newey-West HAC standard errors in parentheses. CP-BRP-'n'y is the estimated ex-ante n year BRP; MWI is the maturity-weighted issuance to nominal GDP ratio; $Corr$ is the dynamic conditional correlation of month returns of the S&P 500 Index and the 10-year Treasury bond index; $MWI \times Corr$ is the interaction term between MWI and $Corr$.

3. Kim-Wright BRP (Survey-based Term Structure Estimates)

   In contrast with the previous measures of BRP, Kim and Wright (2005) use direct survey data to purge the future short rate expectations components from bond yields and hence obtain BRP. Using a Kalman filter framework, they incorporate the monthly 6 and 12 month ahead forecasts of Treasury bill yields from the Blue Chip Financial Forecasts. This is supposed to produce more realistic looking yield curve history. The shortcoming of the KW BRP is that it is a much shorter time series, only available since about 1990, because the survey data did not begin until late 1980s. In table 9, we see that once again a very similar pattern emerges despite being a much shorter sample. The second prediction of the model is also confirmed in table 10.

Table 9: The Time-varying Treasury Supply Effect and the Stock-Bond Correlation: Kim-Wright Survey-based BRP

VARIABLES	(1) KWTP5	(2) KWTP5	(3) KWTP5	(4) KWTP5	(5) KWTP5
MWI	-1.805***	-0.950**	1.983**	2.096***	1.531*
	(0.674)	(0.429)	(0.934)	(0.774)	(0.795)
Stock-Bond Corr		2.498***	-2.430**	-2.410**	-2.569*
		(0.418)	(1.209)	(1.087)	(1.333)
MWI x Corr			**11.450*****	**10.212*****	**10.329*****
			(2.976)	(2.597)	(2.542)
1Y Yield				0.083	
				(0.057)	
sign					0.359
					(0.499)
Constant	1.150***	1.148***	0.009	-0.390	-0.016
	(0.281)	(0.185)	(0.357)	(0.391)	(0.411)
Observations	316	316	316	316	316
Adjusted R-squared	0.15	0.65	0.75	0.76	0.76

Newey-West HAC standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Notes: Newey-West standard errors (48 lags) are shown in the parentheses. KWTP5 is the Kim-Wright 5 year term premium. It is estimated by incorporating survey data into a three factor term structure model; MWI is the ratio between the maturity-weighted issuance and the nominal GDP; *Stock-Bond Corr* is the dynamic conditional correlation of the monthly returns of the S&P 500 Index and the 10-year Treasury bond index; *1Y Yield* is the Treasury constant maturity 1 year nominal yield; *Sign* is a dummy variable that equals to 1 when the stock-bond correlation is positive.

Table 10: The Sensitivity of Supply Effect Increases with the Maturity: Kim-Wright BRP

VARIABLES	(1) KWTP2	(2) KWTP3	(3) KWTP4	(4) KWTP5	(5) KWTP10
MWI	1.024***	1.351*	1.679*	1.983**	2.861***
	(0.313)	(0.777)	(0.887)	(0.934)	(0.982)
Stock-Bond Corr	-1.344***	-1.737*	-2.103*	-2.430**	-3.326**
	(0.405)	(0.997)	(1.145)	(1.209)	(1.383)
MWI x Corr	**7.548*****	**9.239*****	**10.494*****	**11.450*****	**13.441*****
	(0.969)	(2.426)	(2.810)	(2.976)	(3.298)
Constant	0.101	0.059	0.024	0.009	0.177
	(0.124)	(0.307)	(0.344)	(0.357)	(0.369)
Observations	316	316	316	316	316
Adjusted R-squared	0.79	0.78	0.77	0.75	0.67

Newey-West HAC standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Notes. Newey-West HAC standard errors in parentheses. KWTP'n' is the Kim-Wright n year term premium; MWI is the maturity-weighted issuance to nominal GDP ratio; $Corr$ is the dynamic conditional correlation of month returns of the S&P 500 Index and the 10-year Treasury bond index; $MWI \times Corr$ is the interaction term between MWI and $Corr$.

5.2 Inflation Uncertainty

It has been argued that an important source of bond risk premium comes from the inflation uncertainty premium. In particular, high inflation levels are associated with greater inflation uncertainty. While it is know that the level of the nominal short rate is highly correlated with inflation, it is worthwhile to separately control for the inflation uncertainty. Here we capture the uncertainty about long term expected inflation using the difference between the long-term (10 year) government bond yields and the 5-year moving average of real GDP growth rates. Table (11) shows that the main predictions of the model remains robust after controlling for inflation uncertainty. Column 1 shows that the result holds for the MWI measure of supply and column 2 shows that the result continues to hold when we control for the quantity of issuance.

Table 11: Regression on MWI: Inflation Uncertainty

	(1)	(2)
VARIABLES	tp10	tp10
WAM		0.359*
		(0.186)
Corr	-1.529*	-2.647*
	(0.836)	(1.567)
WAM x Corr		**1.749*****
		(0.525)
IssQuant		16.359***
		(3.656)
Infl Uncertainty	0.123***	0.116***
	(0.030)	(0.044)
MWI	4.504***	
	(0.477)	
MWI x Corr	**7.838*****	
	(1.654)	
Constant	-0.356	-2.069***
	(0.223)	(0.577)
Observations	658	658
Adjusted R-squared	0.54	0.57

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

TP10 is the 10 year statistical term premium from Adrian, Crump and Moench (2013); MWI is the maturity-weighted issuance to NGDP ratio; Stock-Bond Corr is the dynamic conditional correlation of month returns of the S&P 500 index and the 10 year Treasury bond index; 1Y Yield is the Treasury constant maturity 1 year nominal yield.

5.3 More Robustness Checks

There is a host of other robustness checks that are relegated to the appendix.

- Quarterly regressions and non-overlapping annual regressions: qualitatively very similar but annual reg has less power.
- Different time sub-samples. In a way, the KW regressions are telling because the KW series starts in 1990 Jan.

6 QE Unwind Application

The Fed is expected unwind about \$180bil of Treasuries in 2018. Without calibrating the model, we can only do a back of the envelope calculation of the expected effect of the QE unwind taking stock-bond correlation into consideration. Assume that the Fed winds proportionally so that its "issuance" has the same maturity structure as its current holdings, we can infer the duration risk from its current holdings. Roughly, an anticipated \$180bil unwinding corresponds to about 10bps an increase in 10 year term premium as opposed to about 25bps not considering the correlation effect. This is mostly a "qualitative" estimate. I'm working on a fully specified discrete VAR to obtain quantitatively meaningful estimates and dynamic effects.

Figure 8: QE Unwind Schedule

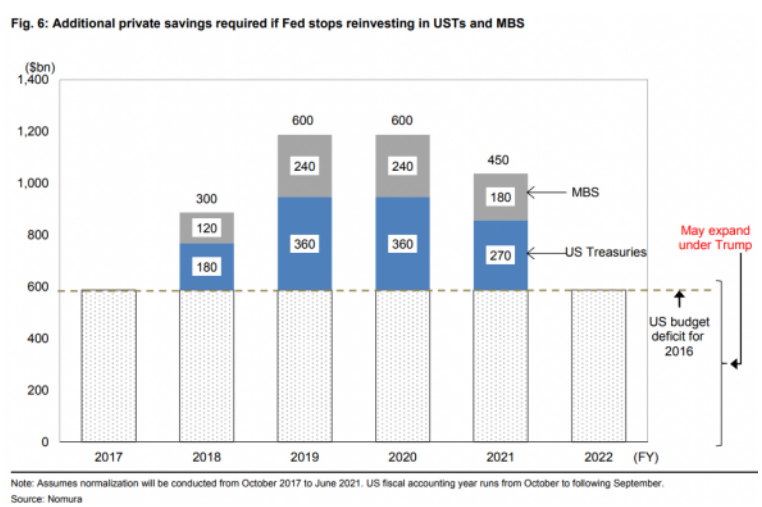


Figure 9: Federal Reserve Portfolio on Sep-13 2017

2. Maturity Distribution of Securities, Loans, and Selected Other Assets and Liabilities, September 13, 2017

Millions of dollars Remaining Maturity	Within 15 days	16 days to 90 days	91 days to 1 year	Over 1 year to 5 years	Over 5 year to 10 years	Over 10 years	All
Loans	47	173	0	0	0	...	220
U.S. Treasury securities (1)							
Holdings	0	38,559	323,378	1,144,904	325,435	633,193	2,465,468
Weekly changes	0	0	- 1	- 3	+ 196	- 12	+ 179
Federal agency debt securities (2)							
Holdings	0	2,366	1,982	62	0	2,347	6,757
Weekly changes	0	0	0	0	0	0	0
Mortgage-backed securities (3)							
Holdings	0	0	1	93	17,608	1,764,644	1,782,346
Weekly changes	0	0	0	0	0	+ 14,792	+ 14,793
Repurchase agreements (4)	0	0	...	...	...	...	0
Central bank liquidity swaps (5)	87	0	0	0	0	0	87
Reverse repurchase agreements (4)	366,719	0	...	...	...	...	366,719
Term deposits	0	0	0	...	...	...	0

7 Conclusion

This paper analyzes the Treasury bond issuances as a driver of the bond risk premium. I provide empirical evidence for a new fact that the effect of Treasury supply on bond risk premium strengthens when the stock-bond return correlation increases in maginitude. This empirical finding is robust to a battery of robustness checks. I rationalize this empirical finding using a modified version of the preferred habitat term structure model. The U.S. Treasury as a borrower supplies bonds across the maturity spectrum with a certain inflexibility that is driven by institutional policy. Risk averse arbitrageurs demand ex ante bond risk premium for absorbing new supply of Treasury bonds to compensate for both the duration risk (interest rate risk) as well as the covariance risk with respect to the existing stocks in their portfolio. The second risk factor appears because the arbitrageurs are unable to quickly shed their exposure to stocks or business cycle risks. As a result, they are unable to unload the additional covariance risks introduced by the new bonds and therefore demand additional (possibly negative) bond risk premium. The effects identified in this paper are new and economically meaningful. They have implications for understanding the impact of shrinking Federal Reserve's balance sheet as well as informing government debt management policy.

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A Mathematical Appendix

In this section, I will show that $A_r(\tau)$, $A_\beta(\tau)$ and $A_s(\tau)$ and $C(\tau)$ in (10) are deterministic functions of τ. In equilibrium, asset markets clear and we obtain (19). Most of what follows is basically the same as the solution in Greenwood and Vayanos (2014), differing by a scaling constant. The arbitrageurs' first order condition for bonds can be written as

$$\mu_t^{(\tau)} - r_t = \sum_{i=r,\beta,s} A_i(\tau) a\sigma_i^2 \int_0^T \left(\zeta_t^{(\tau)} + \theta(\tau)\beta_t\right) A_i(\tau)\, d\tau \tag{22}$$
$$- aA_r(\tau)\left(\int_0^T \left(\zeta_t^{(\tau)} + \theta(\tau)\beta_t\right) A_r(\tau)\, d\tau\right) \bar{x}_t^{(s)} \sigma_s \sigma_r \rho_{r,s}$$
$$- aA_r(\tau)\left(\int_0^T \left(\zeta_t^{(\tau)} + \theta(\tau)\beta_t\right) A_r(\tau)\, d\tau\right) \bar{x}_t^{(s)} \sigma_s^2$$
$$- aA_r(\tau)\left(\int_0^T \left(\zeta_t^{(\tau)} + \theta(\tau)\beta_t\right) A_s(\tau)\, d\tau\right) \sigma_s \sigma_r \rho_{r,s}$$
$$- aA_s(\tau)\left(\int_0^T \left(\zeta_t^{(\tau)} + \theta(\tau)\beta_t\right) A_r(\tau)\, d\tau\right) \sigma_s \sigma_r \rho_{r,s}$$

where

$$\mu_t^{(\tau)} = A_r^{'}(\tau) r_t + A_\beta^{'}(\tau)\beta_t + A_s^{'}(\tau) s_t + C^{'}(\tau) \tag{23}$$
$$- A_r(\tau)\kappa_r(\bar{r} - r_t) + A_\beta(\tau)\kappa_\beta\beta_t - A_s(\tau)(r_t + \sigma_s\xi_s)$$
$$+ \frac{1}{2}A_r(\tau)^2\sigma_r^2 + \frac{1}{2}A_\beta(\tau)^2\sigma_\beta^2 + \frac{1}{2}A_s(\tau)^2\sigma_s^2$$

The LHS of the equality is

$$LHS = A_r^{'}(\tau) r_t + A_\beta^{'}(\tau)\beta_t + A_s^{'}(\tau) s_t + C^{'}(\tau) \tag{24}$$
$$- A_r(\tau)\kappa_r(\bar{r} - r_t) + A_\beta(\tau)\kappa_\beta\beta_t - A_s(\tau)(r_t + \sigma_s\xi_s)$$
$$+ \frac{1}{2}A_r(\tau)^2\sigma_r^2 + \frac{1}{2}A_\beta(\tau)^2\sigma_\beta^2 + \frac{1}{2}A_s(\tau)^2\sigma_s^2 - r_t$$

The RHS of the equality is

$$
\begin{aligned}
RHS = & \sum_{i=r,\beta,s} A_i(\tau)\, a\sigma_i^2 \int_0^T \left(\zeta_t^{(\tau)} + \theta(\tau)\beta_t\right) A_i(\tau)\, d\tau \\
& - aA_r(\tau)\left(\int_0^T \left(\zeta_t^{(\tau)} + \theta(\tau)\beta_t\right) A_r(\tau)\, d\tau\right) \bar{x}_t^{(s)} \sigma_s\sigma_r\rho_{r,s} \\
& - aA_r(\tau)\left(\int_0^T \left(\zeta_t^{(\tau)} + \theta(\tau)\beta_t\right) A_r(\tau)\, d\tau\right) \bar{x}_t^{(s)} \sigma_s^2 \\
& - aA_r(\tau)\left(\int_0^T \left(\zeta_t^{(\tau)} + \theta(\tau)\beta_t\right) A_s(\tau)\, d\tau\right) \sigma_s\sigma_r\rho_{r,s} \\
& - aA_s(\tau)\left(\int_0^T \left(\zeta_t^{(\tau)} + \theta(\tau)\beta_t\right) A_r(\tau)\, d\tau\right) \sigma_s\sigma_r\rho_{r,s}
\end{aligned}
\tag{25}
$$

Collect r_t terms

$$A_r^{'}(\tau) + A_r(\tau)\kappa_r - 1 = A_s(\tau) \tag{26}$$

Collect s_t terms

$$A_s^{'}(\tau) = 0 \;\Rightarrow\; A_s(\tau) = Const. \tag{27}$$

Before we collect the β_t terms we note that the initial conditions, $A_r(0) = A_s(0) = A_\beta(0) = C(0) = 0$ so that $P_t(0) = 1$. In particular,

$$A_s(0) = 0 \;\Rightarrow\; A_s(\tau) = 0 \tag{28}$$

This simplifies the ODEs for $A_r(\tau)$ and $A_\beta(\tau)$ significantly. For $A_r(\tau)$,

$$A_r^{'}(\tau) + A_r(\tau)\kappa_r - 1 = 0 \tag{29}$$

$$\Rightarrow A_r(\tau) = \frac{1 - e^{-\kappa_r\tau}}{\kappa_r} \tag{30}$$

and for $A_\beta(\tau)$,

$$\begin{aligned} A_\beta^{'}(\tau)+A_\beta(\tau)\kappa_\beta =& A_r(\tau)a\sigma_r^2\int_0^T\theta(\tau)A_r(\tau)d\tau \\ &+A_\beta(\tau)a\sigma_\beta^2\int_0^T\theta(\tau)A_\beta(\tau)d\tau \\ &-aA_r(\tau)\left(\int_0^T\theta(\tau)A_r(\tau)d\tau\right)x_t^{(s)}\sigma_s\sigma_r\rho_{r,s} \\ &-aA_r(\tau)\left(\int_0^T\theta(\tau)A_r(\tau)d\tau\right)x_t^{(s)}\sigma_s^2 \end{aligned} \tag{31}$$

The solution to the $A_\beta(\tau)$. For convenience, define

$$Z = a\sigma_r^2 I_r \tag{32}$$

$$I_r = \int_0^T\frac{1-e^{-\kappa_r\tau}}{\kappa_r}\theta(\tau)d\tau \tag{33}$$

$$\begin{aligned} A_\beta^{'}(\tau)+A_\beta(\tau)\left(\kappa_\beta-a\sigma_\beta^2\int_0^T A_\beta(\tau)\theta(\tau)d\tau\right) &= A_r(\tau)Z-A_r(\tau)Z\frac{\sigma_s}{\sigma_r}x_t^{(s)}\rho_{r,s}-A_r(\tau)Z\frac{\sigma_s^2}{\sigma_r^2}x_t^{(s)} \\ &= Z\left(\frac{1-e^{-\kappa_r\tau}}{\kappa_r}\right)\left(1-\frac{\sigma_s}{\sigma_r}\bar{x}_t^{(s)}\rho_{r,s}-\frac{\sigma_s^2}{\sigma_r^2}\bar{x}_t^{(s)}\right) \end{aligned} \tag{34}$$

Define

$$\hat{\kappa}_\beta = \kappa_\beta-a\sigma_\beta^2\int_0^T A_\beta(\tau)\theta(\tau)d\tau \tag{35}$$

$$\hat{\lambda} = 1-\frac{\sigma_s}{\sigma_r}\bar{x}_t^{(s)}\rho_{r,s}-\frac{\sigma_s^2}{\sigma_r^2}\bar{x}_t^{(s)} \tag{36}$$

So we have the simplified formulation

$$A_\beta^{'}(\tau)+A_\beta(\tau)\hat{\kappa}_\beta = Z\hat{\lambda}\left(\frac{1-e^{-\kappa_r\tau}}{\kappa_r}\right) \tag{37}$$

$$A_\beta(\tau) = \frac{Z\hat{\lambda}}{\kappa_r}\left(\frac{1-e^{-\hat{\kappa}_\beta\tau}}{\hat{\kappa}_\beta}-\frac{e^{-\kappa_r\tau}-e^{-\hat{\kappa}_\beta\tau}}{\hat{\kappa}_\beta-\kappa_r}\right) \tag{38}$$

where $\hat{\kappa}_\beta$ solves the following expression

$$\hat{\kappa}_\beta = \kappa_\beta - a\sigma_\beta^2 \int_0^T \frac{Z\hat{\lambda}}{\kappa_r}\left(\frac{1-e^{-\hat{\kappa}_\beta\tau}}{\hat{\kappa}_\beta} - \frac{e^{-\kappa_r\tau}-e^{-\hat{\kappa}_\beta\tau}}{\hat{\kappa}_\beta-\kappa_r}\right)\theta\left(\tau\right)d\tau \quad (39)$$

B Summary Statistics Table

Table 12: Summary Statistics Of Key Variables

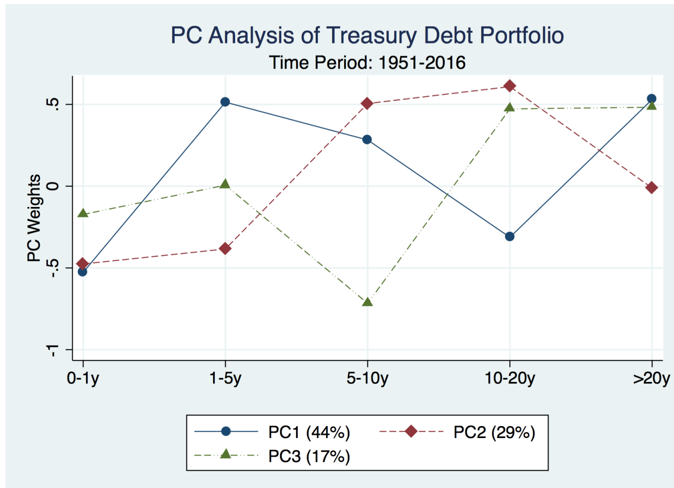
VARIABLES	Units	N	mean	sd	min	max
1Y Yield	percent	672	5.24	3.38	0.10	16.72
ACM 10 Year Term Premium	percent	667	1.65	1.20	-0.67	5.10
KW 10 Year Term Premium	percent	318	0.88	0.89	-0.85	2.84
CP 3 Year Term Premium	percent	612	1.23	2.23	-9.66	9.02
YC Slope (3 Year Minus 1 Year)	percent	667	0.42	0.53	-2.11	1.66
Stock-Bond Correlation (DCC)	decim.	672	0.10	0.15	-0.21	0.37
Stock-Bond Correlation (Rolling)	decim.	672	0.05	0.30	-0.54	0.54
MWI	decim.	670	0.36	0.17	0.09	0.85
WAM Issue	year	671	2.28	0.74	0.76	3.80
Short Share	decim.	671	0.68	0.13	0.45	0.99
WAM Stock	year	672	7.99	1.63	4.72	11.13
Debt-GDP Ratio	decim.	666	0.34	0.15	0.16	0.76

Note: 1Y Yield is the Treasury Constant Maturity 1 year zero coupon yield estimated by the Fed, which I identify as the nominal short rate; ACM is the Adrian, Crump and Moench (2013) bond risk premium; KW is the Kim and Wright (2005) bond risk premium; CP is the Cochrane and Piazzesi (2005) bond risk premium (Excess Return); MWI is the maturity-weighted sum of issuance to GDP ratio, which is the baseline supply measure; WAM issue is the weighted average maturity of the issuance over the following 12 months; Short share is the share of the debt with maturity under 1 year in the total issuance over 12 months, which I use as an alternative measure for maturity choice; WAM Stock is the weight average maturity of the entire stock of Treasuries outstanding at a given time; Debt-GDP ratio is ratio of the total face value of all marketable Treasuries to nominal GDP.

C Plots

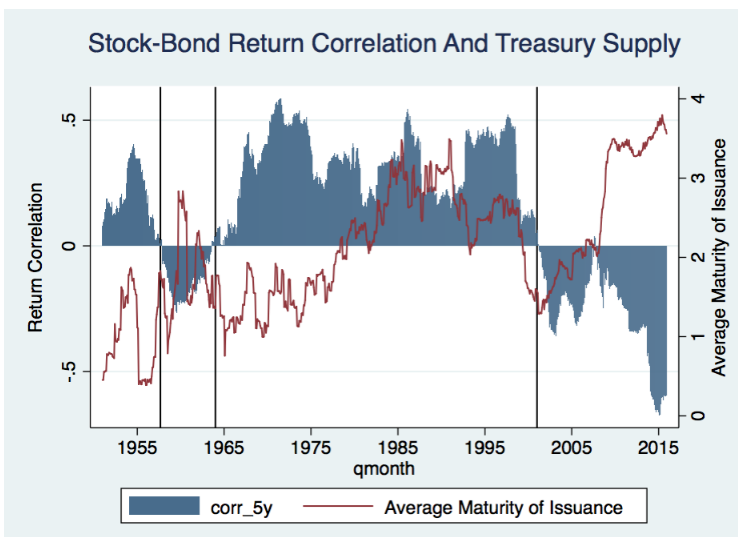
The following plot Figure 16 is taken from Hou (2017). It describes in greater richness the dynamics of the US Treasury debt issuance policy. After encoding the issuance portfolio in 5 maturity bins, I do a principal component analysis of the maturity structure of the Treasury issuance. The first three principal components summarize about 90% of the portfolio variability. About 45% of the movements of the portfolio is between adjustments between the very short term (0-1year) and intermediate term (1-5year and 5-10year) and the adjustments between the long term (10-20year) and the ultra-long term (>20year). Another 30% of the variability comes from between short-medium term and long-ultra long term.

Figure 10: Principal Components of US Treasury Debt Portfolio



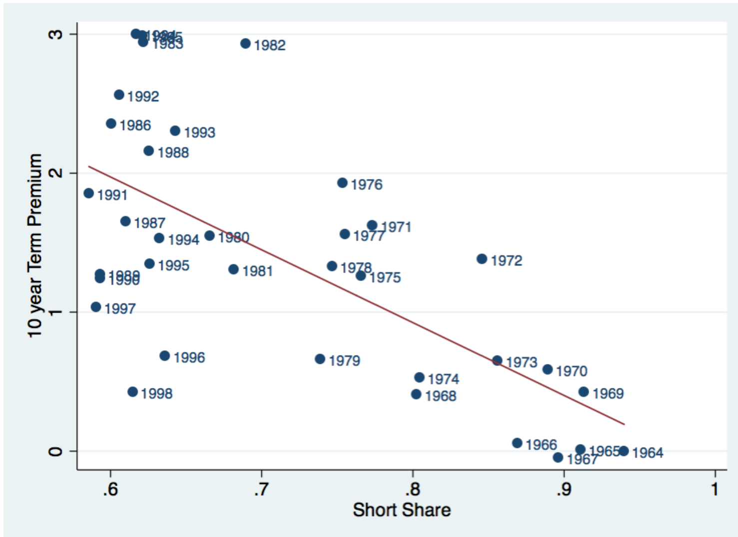
Note: I define five maturity bins: 0 to 1 year, 1 to 5 years, 5 to 10 years, 10 to 20 years and above 20 years. I describe the Treasury issuance portfolio by looking at the ratio of issuance in each maturity bin.

Figure 11: Average Maturity of Issuance and the Stock-Bond Return Correlation: 1951-2016



The data comes from Global Financial Data. Both the stock and bond returns are monthly returns. The stock returns are total returns of the S&P 500 index and the bond returns are the holding period monthly returns computed from the 10 year Treasury Constant Maturity yields.

Figure 12: Short Share and Ten Year Term Premium

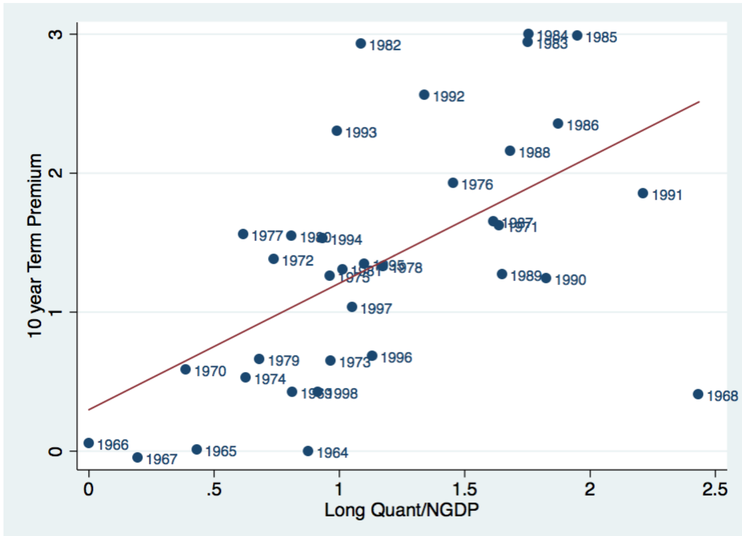


Short Share: 12 month ahead share of short term (maturity ≤ 1 year) debt; TP10: Current ten year term premium from Adrian, Crump and Moench (2013).

D Tables of Results

The following table shows that the baseline results are not changed by using a simple moving window correlation.

Figure 13: Long Quant and Ten Year Term Premium



Long Quant: 12 month ahead sum of long term ($\geq$ 5 year) debt as a share of nominal GDP; TP10: Current ten year term premium from Adrian, Crump and Moench (2013).

Table 13: Regression on MWI: Rolling Corr

VARIABLES	(1) TP5	(2) TP5	(3) TP5	(4) TP5	(5) TP5
MWI	1.348	2.385***	3.000***	3.083***	3.001***
	(0.910)	(0.753)	(0.512)	(0.502)	(0.523)
Stock-Bond Corr		1.908***	-1.205	-1.532	-1.396
		(0.585)	(0.969)	(1.079)	(1.133)
MWI x Corr			7.763***	6.788***	7.816***
			(1.857)	(2.034)	(1.870)
1Y Yield				0.081*	
				(0.044)	
Sign					0.107
					(0.368)
Constant	0.621**	0.153	0.075	-0.367	0.015
	(0.294)	(0.331)	(0.235)	(0.378)	(0.295)
Observations	655	655	655	655	655
Adjusted R-squared	0.07	0.35	0.50	0.53	0.50

Newey-West HAC standard errors in parentheses.
*** p<0.01, ** p<0.05, * p<0.1

TP5 is the 5 year statistical term premium from Adrian, Crump and Moench (2013); MWI is the maturity-weighted issuance to NGDP ratio; Stock-Bond Corr is the 5 Year moving correlation of month returns of the S&P 500 index and the 10 year Treasury bond index; 1Y Yield is the Treasury constant maturity 1 year nominal yield.

The share of short term debt is another measure of maturity of new issuances. Table 16 presents the results from the time series regressions. The results are qualitatively very similar to those of WAM in table 21. Since the higher the share of short term debt and smaller the weighted average maturity of issuance. Unless there is some kind of systematic "curvature" in issuance like short term debt is regularly issued in tandem with very long term debt as an alternative to medium term debt. In the appendix I do a principal component analysis of the maturity structure of issuance. About 52% of the all maturity structure choice is between maturity less than one year and above. The regression results appear to confirm this. While there is a conditional positive correlation between the term premium and WAM, there is similarly a conditional negative correlation between term premium and short share. When the share of short term debt goes from 0 to 100%, the term premium goes down by about 5 percent. Since the short share has a mean of 68% and a standard deviation of 12%, this represents an economically sizable effect.

Table 14: 12-Month Overlapping Monthly Regressions: Short Share and Correlation

VARIABLES	(1) TP5	(2) TP5	(3) TP5	(4) TP5	(5) TP5
Short (0-1y) Share	-2.163*	-3.757***	-3.706***	-3.685***	-3.723***
	(1.233)	(0.837)	(0.719)	(0.672)	(0.748)
Stock-Bond Corr		2.026***	7.400***	6.188***	7.192***
		(0.544)	(1.823)	(2.080)	(1.837)
Short Share x Corr			-8.557***	-7.432**	-8.871***
			(2.877)	(3.143)	(3.017)
TCM 1Y				0.054	
				(0.044)	
Sign					0.261
					(0.326)
Constant	2.585***	3.573***	3.670***	3.376***	3.538***
	(0.938)	(0.601)	(0.530)	(0.543)	(0.559)
Observations	655	655	655	655	655
Adjusted R-squared	0.09	0.41	0.49	0.51	0.49

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

The data ranges between 1961 and 2015. Column 1-4 are overlapping monthly regressions. Column (5) is nonoverlapping annual regressions. The dependent variable is the five year zero coupon term premium from Adrian, Crump and Moench (2013). Short_sh is the sum (by face value) of securities with maturity less or equal to 1 year as a share of all new securities issued in the following 12 months. I express short share in decimals so that an increment of 1 is 100%. I have kept it in this somewhat awkward unit to make the coefficients more readily comparable to that of the sign of the stock-bond return correlation. The sign of the stock-bond return correlation is derived from the 5 year returns correlations. It takes the value of 1 if the correlation is positive. This corresponds to roughly between 1965-2000. TCM 1 year is the Treasury constant maturity 1 year yield from the Federal Reserve.

Table 15: 12-Month Overlapping Monthly Regressions: Short Share and Sign of Correlation

VARIABLES	(1) TP5	(2) TP5	(3) TP5	(4) TP5	(5) TP5
Short Share	-1.836	-5.702***	0.084	-0.661	-0.422
	(1.247)	(1.048)	(1.143)	(1.300)	(1.008)
Short Share x Sign Dummy			-5.786***	-4.604***	-4.582***
			(1.542)	(1.743)	(1.129)
TCM 1 Year				0.063	0.036
				(0.048)	(0.031)
Sign of Stock-Bond Corr			4.884***	3.800***	3.896***
			(1.141)	(1.344)	(0.934)
Constant	2.329**	5.433***	0.549	0.876	0.803
	(0.947)	(0.859)	(0.745)	(0.781)	(0.579)
Observations	667	426	667	667	55
Adjusted R-squared	0.06	0.47	0.47	0.49	0.41

Newey-West HAC standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

The data ranges between 1961 and 2015. Column 1-4 are overlapping monthly regressions. Column (5) is nonoverlapping annual regressions. The dependent variable is the five year zero coupon term premium from Adrian, Crump and Moench (2013). Short_sh is the sum (by face value) of securities with maturity less or equal to 1 year as a share of all new securities issued in the following 12 months. I express short share in decimals so that an increment of 1 is 100%. I have kept it in this somewhat awkward unit to make the coefficients more readily comparable to that of the sign of the stock-bond return correlation. The sign of the stock-bond return correlation is derived from the 5 year returns correlations. It takes the value of 1 if the correlation is positive. This corresponds to roughly between 1965-2000. TCM 1 year is the Treasury constant maturity 1 year yield from the Federal Reserve.

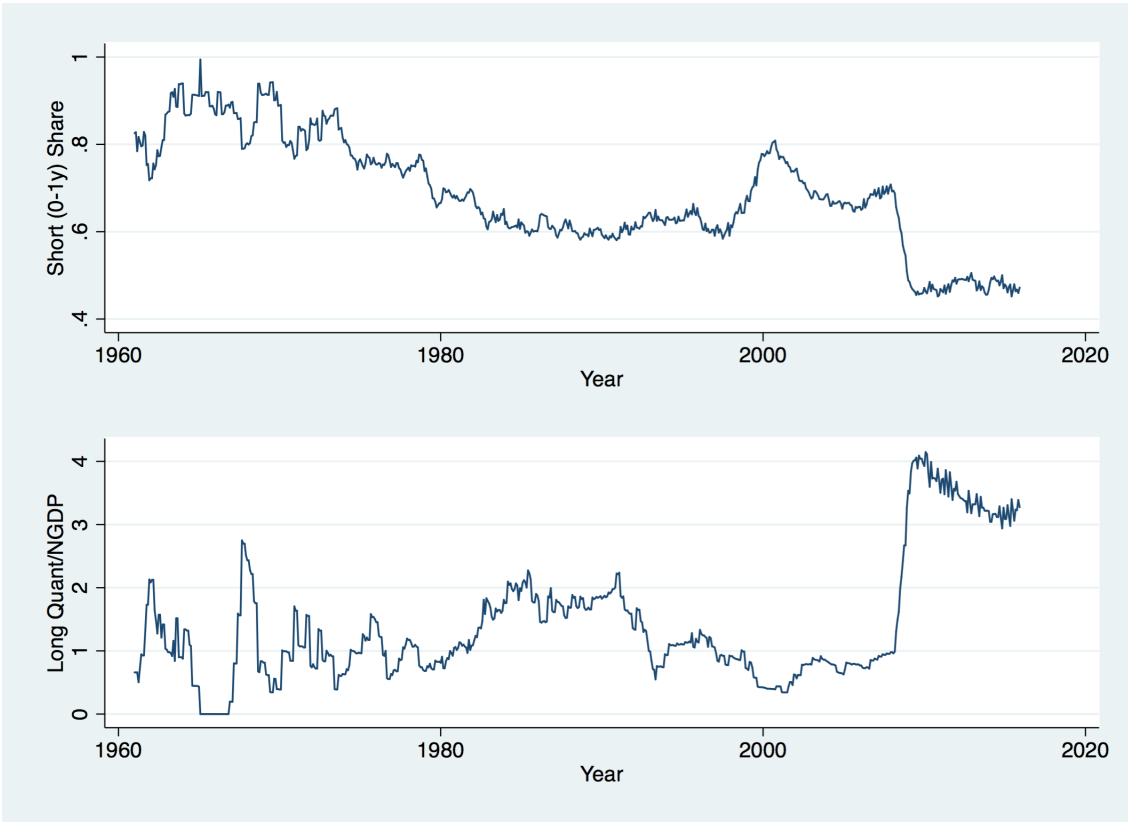
Table 16: 12-Month Overlapping Monthly Regressions: Short Share

VARIABLES	(1) TP5	(2) TP5	(3) TP5	(4) TP5	(5) TP5	(6) TP5
(first) short_sh	-2.163*	-3.747***	-0.227	-1.226	-0.970	-0.811
	(1.233)	(0.794)	(1.098)	(1.646)	(1.256)	(0.955)
Short_sh x Stock-Bond Corr Sign			-5.475***	-3.975*	-4.303**	-4.194***
			(1.509)	(2.337)	(1.713)	(1.068)
Sign of Stock-Bond Corr			4.639***	3.100	3.569***	3.609***
			(1.116)	(1.990)	(1.323)	(0.890)
(first) corr_5y_nocrash		1.902***		0.980		
		(0.458)		(0.913)		
TCM 1 Year					0.062	0.036
					(0.049)	(0.031)
Constant	2.585***	3.557***	0.794	1.722	1.120	1.091**
	(0.938)	(0.574)	(0.704)	(1.212)	(0.738)	(0.532)
Observations	655	655	655	655	655	54
Adjusted R-squared	0.09	0.44	0.47	0.48	0.49	0.41

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

The data ranges between 1961 and 2015. Column 1-4 are overlapping monthly regressions. Column (5) is nonoverlapping annual regressions. The dependent variable is the five year zero coupon term premium from Adrian, Crump and Moench (2013). Short_sh is the sum (by face value) of securities with maturity less or equal to 1 year as a share of all new securities issued in the following 12 months. I express short share in decimals so that an increment of 1 is 100%. I have kept it in this somewhat awkward unit to make the coefficients more readily comparable to that of the sign of the stock-bond return correlation. The sign of the stock-bond return correlation is derived from the 5 year returns correlations. It takes the value of 1 if the correlation is positive. This corresponds to roughly between 1965-2000. TCM 1 year is the Treasury constant maturity 1 year yield from the Federal Reserve.

Figure 14: Plots of Short Share and Long Quant



The short share is the share of the new issuances with maturity less or equal to 1 year to the total amount of new issuances in the next 12 months. The long_quant is the ratio between the total face value of long term debt with maturity greater than 5 years as a share of the nominal GDP.

The reason measures of maturity matter for term premium is that investors demand extra compensation for holding long term bonds. It would be therefore natural to test this hypothesis directly by regressing the term premium on the quantity of long term debt issued. Because the quantity of long term has a trend over decades, I normalize the quantity of new long term debt by nominal GDP. I define long term debt as Treasury having a maturity greater or equal to 5 years. If the term premium is compensation for holding long term bonds, we would expect positive coefficients on the long term debt quantity terms. Indeed that's what we find. For every percentage higher long term issuance as a share of nominal GDP is associated with about 0.8 to 0.9 percent higher term premium.

$$LongQuant_t = \frac{\sum_{n \geq 5y} FVO_{i,t \leq s \leq t+12m}}{NGDP_t} \tag{40}$$

Table 17: 12-Month Overlapping Monthly Regressions: Long Quant and Correlation

VARIABLES	(1) TP5	(2) TP5	(3) TP5	(4) TP5	(5) TP5
Long_quant	0.083	0.278**	0.585***	0.587***	0.590***
	(0.148)	(0.139)	(0.119)	(0.113)	(0.125)
Stock-Bond Corr		1.768***	-0.872	-1.276	-1.258
		(0.624)	(0.851)	(0.901)	(1.214)
Long_quant x Corr			1.709***	1.542***	1.740***
			(0.424)	(0.423)	(0.442)
TCM 1Y				0.076	
				(0.047)	
Sign of Corr					0.215
					(0.457)
Constant	0.986***	0.619**	0.370**	-0.024	0.244
	(0.242)	(0.274)	(0.188)	(0.357)	(0.308)
Observations	655	655	655	655	655
Adjusted R-squared	0.01	0.24	0.41	0.44	0.41

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

The data ranges between 1961 and 2015. Column 1-4 are overlapping monthly regressions. Column (5) is nonoverlapping annual regressions. The dependent variable is the five year zero coupon term premium from Adrian, Crump and Moench (2013). Long_quant is the sum of securities with maturity greater than 5 year as a share of nominal GDP. I express long_quant in percents. The sign of the stock-bond return correlation is derived from the 5 year returns correlations. It takes the value of 1 if the correlation is positive. This corresponds to roughly between 1965-2000. TCM 1 year is the Treasury constant maturity 1 year yield from the Federal Reserve.

Table 18: 12-Month Overlapping Monthly Regressions: Long Quant and Sign of Correlation

VARIABLES	(1) TP5	(2) TP5	(3) TP5	(4) TP5	(5) TP5
Long_quant	0.046	0.954***	-0.037	0.065	0.061
	(0.147)	(0.264)	(0.129)	(0.157)	(0.105)
Long_quant x Sign Dummy			0.991***	0.806***	0.804***
			(0.294)	(0.297)	(0.190)
TCM 1 Year				0.084	0.064
				(0.054)	(0.053)
Sign of Stock-Bond Corr			-0.449	-0.567	-0.453***
			(0.382)	(0.398)	(0.149)
Constant	1.014***	0.227	0.676**	0.300	0.365
	(0.243)	(0.263)	(0.284)	(0.445)	(0.378)
Observations	665	426	665	665	55
Adjusted R-squared	0.00	0.32	0.37	0.41	0.35

Newey-West HAC standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

The data ranges between 1961 and 2015. Column 1-4 are overlapping monthly regressions. Column (5) is nonoverlapping annual regressions. The dependent variable is the five year zero coupon term premium from Adrian, Crump and Moench (2013). Long_quant is the sum of securities with maturity greater than 5 year as a share of nominal GDP. I express long_quant in percents. The sign of the stock-bond return correlation is derived from the 5 year returns correlations. It takes the value of 1 if the correlation is positive. This corresponds to roughly between 1965-2000. TCM 1 year is the Treasury constant maturity 1 year yield from the Federal Reserve.

Table 19: 12-Month Overlapping Monthly Regressions: WAM of Issuance and Correlation

VARIABLES	(1) TP5	(2) TP5	(3) TP5	(4) TP5	(5) TP5
WAM	0.360	0.505***	0.530***	0.525***	0.529***
	(0.227)	(0.182)	(0.127)	(0.124)	(0.132)
Stock-Bond Corr		1.697***	-2.325*	-2.422*	-2.807**
		(0.561)	(1.191)	(1.267)	(1.412)
WAM x Corr			1.584***	1.438***	1.630***
			(0.406)	(0.444)	(0.413)
TCM 1Y				0.050	
				(0.050)	
Sign					0.233
					(0.383)
Constant	0.286	-0.132	-0.094	-0.336	-0.223
	(0.460)	(0.460)	(0.324)	(0.434)	(0.345)
Observations	655	655	655	655	655
Adjusted R-squared	0.08	0.33	0.45	0.47	0.46

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

The data ranges between 1961 and 2015. Column 1-4 are overlapping monthly regressions. Column (5) is nonoverlapping annual regressions. The dependent variable is the five year zero coupon term premium from Adrian, Crump and Moench (2013). WAM is the average maturity (weighted by face value) of the new securities issued in the following 12 months with units in years. The sign of the stock-bond return correlation is derived from the 5 year returns correlations. It takes the value of 1 if the correlation is positive. This corresponds to roughly between 1965-2000. TCM 1 year is the Treasury constant maturity 1 year yield from the Federal Reserve.

Table 20: 12-Month Overlapping Monthly Regressions: WAM of Issuance and Sign of Correlatioin

VARIABLES	(1) TP5	(2) TP5	(3) TP5	(4) TP5	(5) TP5
WAM	0.303	0.931***	-0.154	-0.059	-0.110
	(0.230)	(0.192)	(0.184)	(0.228)	(0.158)
WAM x Sign Dummy			1.085***	0.927***	0.932***
			(0.265)	(0.304)	(0.164)
TCM 1 Year				0.053	0.023
				(0.053)	(0.039)
Sign of Stock-Bond Corr			-1.656***	-1.541**	-1.421***
			(0.598)	(0.635)	(0.315)
Constant	0.383	-0.671*	0.985**	0.634	0.841*
	(0.465)	(0.373)	(0.482)	(0.677)	(0.508)
Observations	667	426	667	667	55
Adjusted R-squared	0.06	0.43	0.45	0.46	0.38

Newey-West HAC standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

The data ranges between 1961 and 2015. Column 1-4 are overlapping monthly regressions. Column (5) is nonoverlapping annual regressions. The dependent variable is the five year zero coupon term premium from Adrian, Crump and Moench (2013). WAM is the average maturity (weighted by face value) of the new securities issued in the following 12 months with units in years. The sign of the stock-bond return correlation is derived from the 5 year returns correlations. It takes the value of 1 if the correlation is positive. This corresponds to roughly between 1965-2000. TCM 1 year is the Treasury constant maturity 1 year yield from the Federal Reserve.

Table 21: 12-Month Overlapping Monthly Regressions: WAM of Issuance

VARIABLES	(1) TP5	(2) TP5	(3) TP5	(4) TP5	(5) TP5	(6) TP5
Average Maturity of Issuance	0.360	0.495***	-0.109	-0.050	-0.015	-0.047
	(0.227)	(0.177)	(0.183)	(0.254)	(0.229)	(0.160)
wam_issue x stock-bond corr sign			1.040***	0.943***	0.884***	0.868***
			(0.264)	(0.356)	(0.305)	(0.160)
Sign of Stock-Bond Corr			-1.592***	-1.605***	-1.473**	-1.303***
			(0.604)	(0.613)	(0.643)	(0.315)
(first) corr_5y_nocrash		1.596***		0.429		
		(0.469)		(0.802)		
TCM 1 Year					0.052	0.024
					(0.054)	(0.038)
Constant	0.286	-0.116	0.921*	0.907*	0.572	0.721
	(0.460)	(0.444)	(0.490)	(0.530)	(0.692)	(0.519)
Observations	655	655	655	655	655	54
Adjusted R-squared	0.08	0.35	0.44	0.44	0.45	0.37

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

The data ranges between 1961 and 2015. Column 1-4 are overlapping monthly regressions. Column (5) is nonoverlapping annual regressions. The dependent variable is the five year zero coupon term premium from Adrian, Crump and Moench (2013). WAM is the average maturity (weighted by face value) of the new securities issued in the following 12 months with units in years. The sign of the stock-bond return correlation is derived from the 5 year returns correlations. It takes the value of 1 if the correlation is positive. This corresponds to roughly between 1965-2000. TCM 1 year is the Treasury constant maturity 1 year yield from the Federal Reserve.

Table 22: Quarterly Issuance Regressions: 1961Q1-2015Q4 Using 2 Year Correlation

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
VARIABLES		Short (0-1y) Share				Average Maturity of Issuance		
10Y Term Premium	-0.038	-0.048***	-0.062***	-0.062***	0.207	0.251**	0.303***	0.304***
	(0.024)	(0.018)	(0.017)	(0.018)	(0.132)	(0.114)	(0.113)	(0.113)
TCM 1 Year			0.014*	0.014*			-0.051	-0.051
			(0.007)	(0.007)			(0.046)	(0.046)
Sign of Stock-Bond Corr		0.130***	0.072*	0.072*		-0.588**	-0.375	-0.375
		(0.044)	(0.043)	(0.043)		(0.276)	(0.281)	(0.281)
Tax Season Dummy				0.030***				-0.265***
				(0.011)				(0.091)
Constant	0.755***	0.679***	0.671***	0.656***	1.879***	2.225***	2.257***	2.389***
	(0.052)	(0.050)	(0.047)	(0.048)	(0.286)	(0.309)	(0.305)	(0.308)
Observations	218	218	218	218	218	218	218	218
Adjusted R-squared	0.10	0.27	0.32	0.33	0.07	0.16	0.18	0.19

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

LHS variables are respectively one quarter forward the share of short term debt (maturity 1 year or less) and the face value weighted average maturity of new debt issued. The regressors are contemporaneous observations. Ten year term premium is from Adrian, Crump and Moench (2013). Treasury constant maturity 1 year interest rate is used to proxy for the level of nominal interest rate. The sign of stock and bond returns is taken from the sign of the 5 year moving average correlation between monthly stock returns and monthly bond returns. The tax season dummy is one for the second and fourth quarters, when personal and corporate income tax receipts come into the Treasury.

Table 23: Quarterly Regressions of Issuance Maturity: 1961Q1-2015Q4 Using 5 Year Correlation

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
VARIABLES		Short (0-1y) Share				Average Maturity of Issuance		
10Y Term Premium	-0.038	-0.055***	-0.063***	-0.064***	0.207	0.275**	0.315***	0.316***
	(0.024)	(0.019)	(0.017)	(0.017)	(0.132)	(0.119)	(0.113)	(0.113)
TCM 1 Year			0.010	0.011			-0.049	-0.050
			(0.008)	(0.008)			(0.052)	(0.052)
Sign of Stock-Bond Corr		0.150***	0.102*	0.102*		-0.594*	-0.371	-0.365
		(0.051)	(0.058)	(0.058)		(0.322)	(0.377)	(0.377)
Tax Season Dummy				0.029***				-0.262***
				(0.011)				(0.091)
Constant	0.755***	0.680***	0.671***	0.657***	1.879***	2.181***	2.220***	2.349***
	(0.052)	(0.049)	(0.047)	(0.047)	(0.286)	(0.308)	(0.304)	(0.306)
Observations	218	218	218	218	218	218	218	218
Adjusted R-squared	0.10	0.32	0.34	0.35	0.07	0.16	0.17	0.19

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

LHS variables are respectively one quarter forward the share of short term debt (maturity 1 year or less) and the face value weighted average maturity of new debt issued. The regressors are contemporaneous observations. Ten year term premium is from Adrian, Crump and Moench (2013). Treasury constant maturity 1 year interest rate is used to proxy for the level of nominal interest rate. The sign of stock and bond returns is taken from the sign of the 5 year moving average correlation between monthly stock returns and monthly bond returns. The tax season dummy is one for the second and fourth quarters, when personal and corporate income tax receipts come into the Treasury.

Table 24: Monthly and Annual Regressions of Issuance Maturity Measures: 1961 Jan-2015 Dec Using 5 Year Correlation

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
VARIABLES	Short (0-1y) Share				Average Maturity of Issuance			
	Monthly Overlapping			Annual	Monthly Overlapping			Annual
10Y Term Premium	-0.037**	-0.056***	-0.064***	-0.056***	0.201*	0.278***	0.316***	0.281***
	(0.018)	(0.015)	(0.015)	(0.012)	(0.105)	(0.097)	(0.097)	(0.078)
TCM 1 Year			0.010				-0.046	
			(0.007)				(0.045)	
Sign of Stock-Bond Corr		0.151***	0.106**	0.153***		-0.640**	-0.432	-0.643***
		(0.040)	(0.048)	(0.031)		(0.256)	(0.316)	(0.198)
Constant	0.748***	0.674***	0.665***	0.674***	1.931***	2.245***	2.285***	2.231***
	(0.039)	(0.037)	(0.036)	(0.029)	(0.221)	(0.236)	(0.238)	(0.183)
Observations	655	655	655	54	655	655	655	54
Adjusted R-squared	0.12	0.40	0.43	0.39	0.10	0.25	0.27	0.23

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

LHS variables are respectively 12 months forward the share of short term debt (maturity 1 year or less) and the face value weighted average maturity of new debt issued. Column 4 and column 8 are non-overlapping annual regressions using fiscal years (Oct). Results are not qualitatively similar to using calendar years. The regressors are contemporaneous observations. Ten year term premium is from Adrian, Crump and Moench (2013). Treasury constant maturity 1 year interest rate is used to proxy for the level of nominal interest rate. The sign of stock and bond returns is taken from the sign of the 5 year moving average correlation between monthly stock returns and monthly bond returns.

E The Non-Market Drivers of the US Debt Issuance Policy

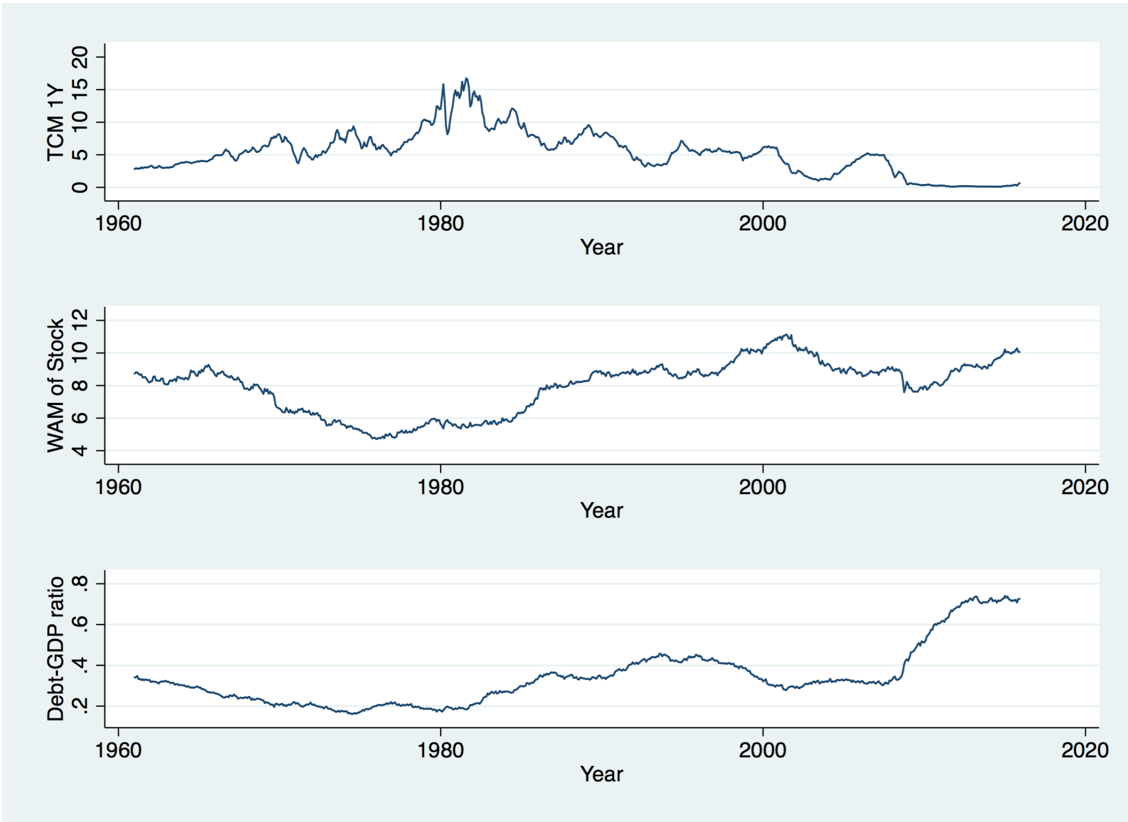
E.1 Overview

As seen in Table **??** and Figure 2, the portfolio has gone through significant evolution over the course of last century. Over time, the US federal government has taken on different levels of debt (measured as a share of GDP) and significantly different composition. In this paper, I am primarily focused on the maturity profile of the debt and am largely ignoring the policy choices such as callability and other option features[18] or indexation[19] Over time, the average maturity of government has significantly trended down while the absolute quantity of the debt has grown exponentially. There are distinctly two paradigms. Up until the end of world world two (or pre-war era henceforth), the US government debt was less regular or well-structured.

[18]Until mid 1980s, the Treasury regularly issued callable bonds, which allows the Treasury to redeem the bond prior to maturity. This option feature apart from clearly having implications on the value of the debt, also means that the bond's effective maturity may be shorter than the stated value. Since the Treasury rarely actually exercised the call option on its debt, I have decided not to emphasize this particular feature.

[19]Treasury Inflation Protected Securities (TIPS), which are introduced in 1997, are offered in 5, 10 and 30 year maturities. The TIPS, which have grown significantly since inception, remain a small portion of the overall Treasury debt portfolio ($1.2 trillion out of $13.9 trillion marketable debt). While indexation affects the market value of the debt, it does not directly affect maturity of the debt.

Figure 15: Plots of Ancillary Time Series Variables



TCM1Y is the one year Treasury constant maturity yield estimated by the Federal Reserve; WAM_Stock is the weighted average maturity of the stock of marketable debt outstanding; the debt to GDP ratio is the ratio between the total face va value of the marketable debt and the nominal GDP.

It tends to consist mostly of one-off long term bonds to finance specific expenditures such as the war or the Panama canal project. Between 1917 and the end of world war two, Congress gradually delegated increasingly more borrowing power to the Treasury within the debt limit[20] Since the end of the war, the US Treasury debt management has gradually modernized and the portfolio too has stabilized. Because of the burgeoning and persistent borrowing need, the Treasury has come to increasingly rely on frequent auctions of short term debt[21]. Since the late 70s, the Treasury has also officially given up on tactical issuance and transitioned towards a policy of "regular and predictable", where the Treasury would conduct regular prescheduled auctions of debt securities, actively solicit market demand information

[20]While Congress has continued to set a limit or ceiling on the aggregate quantity of debt the Treasury can take on, it has also periodically raised that ceiling whenever it was about to be breached. Since 2001, the debt limit has been raised 15 times with intermittent political crisis threatening failure to raise the debt limit.

[21]Garbade, the Birth of a market

and choreograph supply schedules. As can be seen in 2, the postwar Treasury debt portfolio tends to consist of substantially more short- and medium-term debt with relatively stable portfolio weights. Nevertheless there is still substantial and systematic variability in the debt portfolio over time. In fact, I will show that the debt issuance robustly responds to rollover risk and average maturity of the debt stock but not to market prices or expectation of market prices.

E.2 Regression Analysis of Government Issuance Policy

Table 25: Predictive Regression of WAM of Issuance: 1951-2016, Face Value of Debt Stock

VARIABLES	(1) Year 1951-2016 WAM of Issuance	(2) Year 1951-1983 WAM of Issuance	(3) Year 1983-2016 WAM of Issuance	(4) Year 1951-2016 Non-OL WAM of Issuance
TCM 1 Year	0.394***	0.290***	0.217**	0.386***
	(0.095)	(0.094)	(0.088)	(0.086)
DGDP	0.869***	1.025***	0.609***	0.863***
	(0.088)	(0.279)	(0.071)	(0.078)
WAM Stock	-0.246***	-0.470***	-0.437***	-0.247***
	(0.094)	(0.136)	(0.091)	(0.083)
Constant	2.152***	1.962***	2.498***	2.153***
	(0.068)	(0.137)	(0.067)	(0.058)
Observations	759	369	402	63
Adjusted R-squared	0.69	0.46	0.80	0.66

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

The baseline regressions (column 1-3) are overlapping monthly predictive regressions. The dependent variable is the weighted average maturity of debt issued in the following 12 months. The independent variables are the current nominal interest rate (Treasury constant maturity 1 year), standardized marketable debt (face value) to GDP ratio, standardized weighted average maturity of all outstanding debt. Because overlapping regressions induce autocorrelation, I use Newey-West HAC standard errors. As a further check, I run a non-overlapping annual regression. There are 12 ways of running an annual regression. I display here the results from using fiscal year or Oct to Oct. Results from using calendar year are very similar.

I test the cost minimization model of debt management using predictive regressions. Specifically, I predict measures of Treasury issuance policy choice with contemporaneous variables. Because Treasuries of different maturities are auctioned on different schedules, in particular shorter maturity debt is auctioned more frequently than longer maturity debt, issuance policy stance can be only be accurately gauged from looking over a period of time. For this reason, a contemporaneous regression is not feasible: it's either regression on past or future information. I have chosen a predictive specification because I believe it best mimics the problem faced by policymakers at the US Treasury. This specification is equivalent to asking the Treasury officials to make a complete issuance schedule for the following year using current market and macro information. I begin by looking at weighted average maturity of new debt issues.

F Measuring Maturity Structure

$$WAM_t = \frac{\sum_i^N FVO_{i,t\leq s\leq t+12m} \cdot \text{Maturity}_{i,t\leq s\leq t+12m}}{\sum_i^N FVO_{i,t\leq s\leq t+12m}} \tag{41}$$

An alternative measure of maturity structure is looking at the share of short term debt in the total amount of debt issued in the following 12 months. I define short term debt as securities with a maturity less than a year.

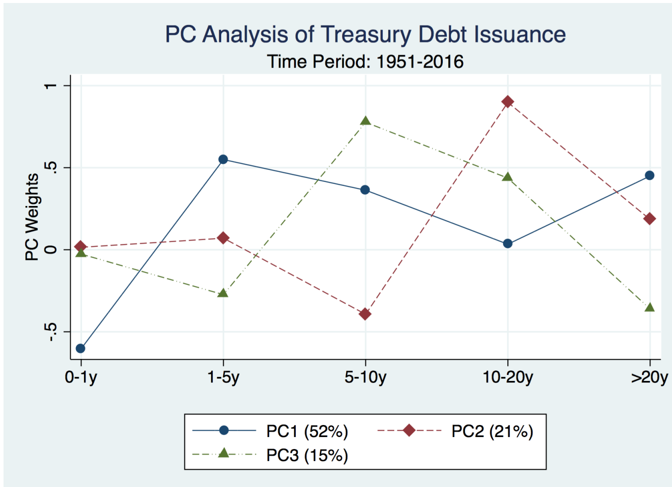
$$ShortShare_t = \frac{\sum_{n\leq 1y} FVO_{i,t\leq s\leq t+12m}}{\sum_i FVO_{i,t\leq s\leq t+12m}} \tag{42}$$

Because the Treasury regularly rolls over maturing debts, new issuance is really a sum of maturing debt and new issuances financing new deficits. Since I am looking at issuances within a short horizon, most of the maturing debt will be either Treasury bills or highly illiquid long term bonds with very short time to maturity. Longer weighted average maturity of new issuances therefore also means greater amount of new long term bonds needs to be absorbed. The same goes for short term share.

I focus on the Treasury new issuances as measure of Treasury policy between 1951 and 2016. At the outset, because issuance maturity choice is highly multi-dimensional, it is not clear which empirical measures should be used. For example, when the government wants to issue more net debt to finance a certain deficit, it could issue uniformly across maturities or let a certain amount of short term debt mature while issuing some long term debt or it could even let a certain amount of short term debt and maturing long term debt mature and issue a certain amount of medium term debt. In order to capture the dynamics of the vectors of portfolio weights, I apply a principal component analysis to the bond issuance. I divide up the issuance into five maturity bins: 0 to 1 year, 1 to 5 years, 5-10 years, 10-20 years and more than 20 years. I define the issuance shares on a monthly basis by the shares of new debt securities issued within a given maturity bin as a share of total amount of debt issued in the next 12 months. I use 12 months[22] because that is a long enough of a time period for every maturity to have a chance to be issued. The results are displayed in figure 16. The PCA results are not as easily interpretable as the PC analysis of the term structure of interest rates, where components can be readily interpreted as "level", "slope" and "curvature". Nevertheless, we can derive some significant insights. The first principal component (PC) explains about 52% of variations in the issuance vectors. There is a significant negative weight on 0-1 year and there are positive weights on all bins except the medium long term bin (10-20 years). I interpret this as saying that about 50% of the issuance policy is about trading off between very short term debt and long term debt. This can be roughly interpreted as a "slope" factor between short (0-1 year) and long term debt (>1 year) or a "level" factor for >1year debt. The second PC explains 21% of the issuance vectors. There are significant weights on 5-10 years and 10-20 years. I interpret this as a trade-off between a choice between issuing intermediate versus the very long term debt. This can be interpreted roughly as a slope factor within the long (>1 year) debt. The third PC explains 15% of the variations and has negative weights on 1-5year and >20year bins and positive weights on 5-10year and 10-20year bins. The trade-off here is between very short/ultra-long term debt and the intermediate/long-term debt. This factor resembles a "curvature" factor for the long term (>1 year) debt where the Treasury could try to push (or do the opposite) maturity towards the center (5-20) by issuing more in the middle and less on the "edges" (1-5 and >20). The three factors taken together suggest that the Treasury apart from deciding how much very short term debt (bills) to issue also tries to manipulate the issuance patterns to achieve a certain maturity target. This exercise confirms that it is reasonable to capture the Treasury's debt policy by either looking at short debt shares or the average maturity of debt issuance and potentially the higher order moments such as the variance of issuance maturities.

[22] I vary this time span to 6 month and 24 months, which I include in the appendix. The results remain qualitatively unchanged.

Figure 16: Principal Components of US Treasury Debt Portfolio



I describe the Treasury debt issuance by first dividing new issues into five bins by maturity: 0 to 1 year, 1 to 5 years, 5 to 10 years, 10 to 20 years and above 20 years. I then calculate the quantity issued in each bin as a share of the total quantity issued in the previous 12 months. The first three principal components summarize about 90% of the portfolio variability. The first component (52% of issuance movements) consists of a choice between very short term debt and medium or long term debt. The second component (21%) consists of a choice between medium term (5-20 year) debt and short- or ultra-long term debt.