Limits to Arbitrage and Mispricing in TIPS*

Lorenzo Bretscher
London School of Economics†

Abstract

This paper examines limits to arbitrage and mispricing in Treasury protected securities (TIPS). To this end, I construct two different measures of disparity in bond prices from the smooth yield curve. I find that deviations in prices are highly correlated for different maturities and also between nominal Treasury bonds and TIPS. This suggests that arbitrage capital is efficiently allocated across markets and also along the yield curve. I then study the relative mispricing of nominal bonds and TIPS. While flight-to-liquidity explains well the mispricing for nominal bonds it does not for TIPS. In fact, TIPS mispricing is driven by short-term Treasury bond liquidity and the slope of the term structure of expected inflation. Moreover, TIPS mispricing predicts short-term excess returns of TIPS during the crises. This findings can be rationalized with investors who opt for more liquid nominal bonds whenever the short-term expected inflation is very low, i.e. short-term nominal bonds and short-term TIPS are close to perfect substitutes.

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†Department of Finance, Email: l.p.bretscher@lse.ac.uk

I. Introduction

The US Treasury has been issuing Treasury Inflation Protected Securities (TIPS) since 1997. Ever since the market for TIPS has been growing and corresponds nowadays roughly to ten percent of total marketable debt in the US and more than 3.5 percent of US GDP. TIPS seem in many respect very similar to nominal bonds. In fact, the inflation-indexing feature of TIPS is the only noteable difference in terms of security design. Nevertheless, the academic literature has reported striking differences between nominal bonds and TIPS in terms of pricing (Fleckenstein, Longstaff, and Lustig (2014)) and liquidity (for example D'Amico, Kim, and Wei (2010), Campbell, Sunderam, and Viceira (2013), and Pflueger and Viceira (2011) among others). In this paper, I compare within-market liquidity and security mispricing between nominal bonds and TIPS by exploiting information in security prices, i.e. I examine daily yield and price deviations from the smooth yield curve. I find that within-market liquidity in TIPS and nominal bonds behaves very similar over my sample period. However, security specific mispricing is very different for the two asset classes. While mispricing is well explained by flight-to-liquidity behavior for nominal bonds, TIPS mispricing is not. I show that TIPS mispricing is related to the slope of the term structure of expected inflation. Moreover, I find evidence for the slow-moving capital hypothesis.

I study within-market liquidity and mispricing by exploiting information in prices. To this end, I construct two different measures of deviations from a smooth yield curve and I find that these deviations are particularly large during times of market stress. The intuition is similar to Hu, Pan, and Wang (2013) who argue that the abundance of arbitrage capital during normal times helps smooth out the yield curve and keep the average dispersion low. This seems to be a reasonable assumption given the presence of many proprietary trading desks at investment banks and hedge funds that are dedicated to arbitrage across different habitats on the yield curve.[1] During times of economic distress and low liquidity, the lack of arbitrage capital sets a limit to the arbitrage activity of proprietary desks and hedge funds. This leads to more freely moving prices and yields

[1]Vayanos and Vila (2009) model the interaction between habitat investors and risk-averse arbitrageurs and its impact on bond yields

along the yield curve which, in turn, leads to more noise and a higher dispersion in the yield curve.

The first step of my analysis closely follows Hu, Pan, and Wang (2013) who construct the cross-sectional average of the squared pricing error in the yield space as a time-series measure of liquidity. Whenever this measure is high, yields are relatively dispersed which suggests that the arbitrage desks cannot effectively arbitrage along the yield curve. Hence, the measure captures the availability of arbitrage capital in a market. Hu, Pan, and Wang (2013) note that this could also be understood as an accurate approximation for overall market liquidity given that US Treasury markets are very sizeable and liquid. Given the well documented fact that overall liquidity in TIPS is lower than in nominal bonds, especially during earlier years and the recent financial crisis, however, I stick to the more narrow interpretation of the measure linked to arbitrage capital. Since the measure focuses on price and yield formation within TIPS or nominal bonds separately, I will refer to it as within-market liquidity or liquidity. Because the different measures rely exclusively on yield curve dispersion in each market separately, a comparison of the measure does not suffer from changes in the relative liquidity between TIPS and nominal bonds.

The comparison of the measures reveal information about how shocks to arbitrage capital affect nominal and real sovereign bond markets. The liquidity in TIPS and nominal bonds is highly correlated both in levels and in changes. This suggests that even in times of shortages in arbitrage capital, the allocation of this capital is efficient. Put differently, funding liquidity seems to co-move extensively across markets. Moreover, calculating the illiquidity measures for short- and long-term securities reveals that liquidity shocks affect the yield curve similarly across different horizons. This is consistent with arbitrage desks and hedge funds which take advantage of arbitrage opportunities along the yield curve. Finally, the time periods from January 1, 2001 to July 1, 2003 and from July 1, 2008 to January 1, 2010 are especially illiquid. Not surprisingly, this corresponds fairly well with the aftermath of the Dotcom crises including 9/11 and the recent financial crisis, respectively.

In a second step, I examine deviations in the price space from the yield curve similar to Musto, Nini, and Schwarz (2014). I refer to this measure of pricing errors as mispricing. This allows me to understand the drivers of the direction and magnitude of each security's individual pricing error. Since the pricing errors are not squared before averaging, the mispricing measure can take either positive or negative values. A positive (negative) value corresponds to securities which are, on average, above (below) the smoothly fitted yield curve, i.e. they are too expensive (cheap). Another interpretation of this measure could be based on demand and supply. Under the assumption that short-term supply is fixed, a positive (negative) value would be associated with high (low) demand for specific securities. Such an interpretation is helpful when thinking about potential explanations for the mispricing and investors' preferences. Looking at within-market mispricing allows me to compare the mispricing of nominal bonds and TIPS directly.[2] As a consequence, direct statements about the interaction of the two markets are not possible with my data.

In my analysis of mispricing, I differentiate between short- and long-term securities. I find that there are fundamental differences in mispricing between nominal bonds and TIPS. On average, short-term nominal bonds trade at a premium compared to long-term nominal bonds. The spread between the two time series widens dramatically during illiquid periods. For TIPS, however, this seems only to be true for liquid periods. During illiquid periods, the opposite is true: long-term TIPS trade at a premium compared to short-term TIPS. An analysis of the mispricing on the security level shows that the mispricing in nominal bonds is well explained by differences in liquidity differences in short- and long-term nominal bonds. This is consistent with Musto, Nini, and Schwarz (2014) who show that the prices of liquid ten year Treasury notes and illiquid 30-year Treasury bonds diverged substantially during this period. They argue that the widening of this spread can be attributed to a liquidity premium similar to the flight-to-liquidity premium reported by Longstaff (2004). However, the TIPS mispricing cannot be explained by flight-to-liquidity. If anything, the results suggest that TIPS investors have a preference for illiquidity. Moreover, TIPS mispricing suggests that investor attach a

[2]In fact, my analysis is not contaminated by the well-established fact that the relative liquidity of nominal bonds and TIPS is time-varying and spiked during the recent financial crisis.

higher value to the deflation option implicitly included in TIPS during the recent financial crisis. This is consistent with the findings of Grishchenko, Vanden, and Zhang (2011).

The rest of the empirical analysis focuses on mispricing in TIPS. While the difference between long- and short-term TIPS mispricing is unrelated to aggregate market liquidity and funding liquidity measures, it is weakly related to short-term liquidity in nominal Treasury bonds. Moreover, the mispricing can be explained by the slope of the term structure of expected inflation. Both these findings are consistent with investors who opt for the more liquid nominal bonds whenever the short-term expected inflation is very low, i.e. short-term nominal bonds and short-term TIPS are close to perfect substitutes. This hypothesis if further strengthened by the fact that the slope of the term structure of expected inflation predicts TIPS mispricing. In addition, mispricing is unrelated to the supply of Treasury bonds and TIPS and Treasury market liquidity. Finally, my results show evidence for the slow-moving capital hypothesis. In particular, lagged total capital available proxied by lagged excess stock and bond returns predict mispricing.

To the best of my knowledge, this paper is the first to analyse the mispricing within the TIPS market using pricing errors relative to daily smooth yield curves.

Literature Review

This paper is related to different areas of the academic finance literature. Most importantly, it is closely related to the literature on mispricing and limits to arbitrage in Treasury markets. For obvious methodological similarities the paper is closely related to the study by Hu, Pan, and Wang (2013). Further, Fleckenstein, Longstaff, and Lustig (2014) analysed mispricing between TIPS and nominal bonds and identified possible arbitrage opportunities. Musto, Nini, and Schwarz (2014) examine mispricing purely in nominal bonds and also detect persistent arbitrage opportunities during the financial crises. In addition, the paper is related to the literature on funding liquidity. Brunnermeier and Pedersen (2009) provide a model that links an asset's market liquidity and traders' funding liquidity. Malkhozov, Mueller, Vedolin, and Venter (2014) calculate and compare the funding liquidity across different countries. They find extensive correlation among countries and construct a global factor. Moreover, they show that this is a priced factor in their funding liquidity CAPM.

My paper is also related to a plethora of empirical papers that study flight-to-safety in equity and bond markets. Focussing on fixed-income markets, Ericsson and Renault (2006) develop a structural bond valuation model to simultaneously capture liquidity and credit risk. The positive correlation between illiquidity and default components of yield spreads in U.S. corporate bond data is consistent with both flight-to-quality and flight-to-liquidity. Favero, Pagano, and von Thadden (2010) propose a model in which a bond's liquidity premium depends both on its transaction cost and on investment opportunities. The model implies that a simultaneous increase in transaction costs (i.e. illiquidity) and aggregate risk can lead to flight to liquidity. Longstaff (2004) empirically determines a flight-to-liquidity premium present in U.S. Treasury bonds. He measures the premium by comparing Treasury bond prices with prices of bonds issued by Refcorp, a U.S. Government agency, which are guaranteed by the Treasury. Finally, Beber, Brandt, and Kavajecz (2009) study flight-to-quality and flight-to-liquidity in European bond markets by examining yield spreads (relative to a common Euro-LIBOR yield curve) and order flow for ten Euro-area countries with active sovereign debt markets. They show that, in times of economic distress, investors are more concerned about liquidity than credit quality which leads to flight-to-liquidity.[3]

Finally, the paper is loosely related to studies about the value of the deflation option embedded in TIPS. Grishchenko, Vanden, and Zhang (2011) calculate the value of these options on a security level and generate an option index. The index shows significant time variation and a prominent spike at the onset of the financial crisis. Christensen, Lopez, and Rudebusch (2012) construct probability forecasts for episodes of price deflation using yields in nominal Treasury bonds and TIPS. They identify tow "deflation fears": a mild one following 2001 and a more serious one starting in late 2008.

[3]Vayanos (2004) examines flight-to-quality and flight-to-liquidity phenomena for equity markets theoretically . Among others Pastor and Stambaugh (2003), Acharya and Pedersen (2005) and Goyenko and Sarkissian (2014) explore the topic empirically.

The remainder of the paper is organized as follows. Section II. explains the methodology applied to estimate the daily yield curves, the construction of the illiquidity and mispricing measures, and details the data. In section III., I report the empirical results and discuss them in three subsections. Section IV. performs various robustness tests. Finally, section V. summarizes the findings and concludes.

II. Curve Fitting, Noise Measures and Data

A. Curve Fitting

This section explains in detail the methodology applied to fit the daily term structures both for TIPS and for nominal bonds. Since the Treasuries only issue a limited number of securities with different maturities and coupons, one needs to impose a structure in order to estimate a continuous yield curve. The different estimation methods to back out zero-coupon yield curves from coupon-bearing bond prices can be broadly classified into spline-based and functional-based models. Spline-based methods rely on piecewise polynomial functions that are smoothly joined at selected knots to approximate the yield curve (see e.g. McCulloch (1975)). In this paper, however, I follow the estimation procedure of Nelson and Siegel (1987), a popular model belonging to the class of function-based models. The Nelson-Siegel (NS) model assumes that the instantaneous forward rates n years ahead are characterized by a continuous function with only four parameters:

$$f_t(n,0) = \beta_0 + \beta_1 \exp(-n/\tau_1) + \beta_2 (n/\tau_1) \exp(-n/\tau_1), \tag{1}$$

where n denotes the time to maturity and $b = (\beta_0, \beta_1, \beta_2, \tau_1)$ are model parameters to be estimated. This function implies that the instantaneous forward rates begin at horizon zero at the level $\beta_0 + \beta_1$ and eventually asymptote to the level of β_0. In between, the forward rates can have a "hump", whose magnitude and sign is determined by the parameter β_2 and the location is is given by the parameter τ_1. In order to model nominal interest rates, a proper set of parameters must satisfy the conditions that $\beta_0 > 0$, $\beta_0 + \beta_1 > 0$, and $\tau_1 > 0$. This needs not necessarily hold in the case of the real yield curve since real interest rates can take negative values. Since the NS model is given in terms of instantaneous forward rates we have to integrate and average to get an expression for the zero coupon yields over a maturity of n-years:

$$y_t(n) = \beta_0 + \beta_1 \frac{1 - \exp(-\frac{n}{\tau_1})}{\frac{n}{\tau_1}} + \beta_2 \left[\frac{1 - \exp(-\frac{n}{\tau_1})}{\frac{n}{\tau_1}} - \exp(-\frac{n}{\tau_1}) \right], \qquad (2)$$

and from these yields one can compute the discount function at any horizon.

In the NS model, forward rates will tend to start at the current short-term rate that is largely determined by the current monetary policy setting (the starting point), will be governed at intermediate-horizons by expectations of the business cycle, inflation, and corresponding monetary policy decisions (the hump), and will end up at a steady-state level (the asymptote) (Gürkaynak, Sack, and Wright, 2007). Note that the NS functional form sometimes has difficulty fitting the entire term structure due to convexity which tends to pull down the yields on longer-term securities.[4] For that reason, Svensson (1994) develops a more flexible extension of the model with six parameters. The NS model is nested in the Nelson-Siegel-Svensson (NSS) model.[5] Although the NSS functional form is more flexible and allows for a second "hump" in the forward rate curve, I rely on the NS model to fit the daily nominal and real yield curves for two main reasons. (i) The second "hump" in the NSS model is not well defined unless we have enough long-term securities. Given the relatively few securities available for fitting the real yield curve allowing for a second hump might do more harm than good. (ii) Since both the US Treasury and the UK government started to issue inflation-linked securities only fairly recently there are only very few security prices available on many days of my estimation period. Estimating the more restricted NS model alleviates over-fitting concerns and allows for estimation with fewer securities which, ultimately, leads to a longer time series of the noise measures.

[4] Mainly securities with remaining maturities of 25 years or more might be problematic

[5] The instantaneous forward rates in the NSS model are governed by six parameters according to the following functional form:

$$f_t(n, 0) = \beta_0 + \beta_1 \exp(-n/\tau_1) + \beta_2 (n/\tau_1) \exp(-n/\tau_1) + \beta_3 (n/\tau_2) \exp(-n/\tau_2).$$

When β_3 is set to zero the yield curve collapses to the NS yield curve.

Finally, I estimate parameters $b_t = (\beta_0, \beta_1, \beta_2, \tau_1)$ for each day t by minimizing the weighted sum of the squared deviations between the actual and model-implied prices:[6]

$$b_t = \underset{b}{\operatorname{argmin}} \sum_{i=1}^{N_t} ((P^i(b) - P_t^i) \times \frac{1}{D_i})^2 \tag{3}$$

where $P^i(b)$ is the model-implied price for bond i given model parameters b and D_i is the Macaulay duration for bond i. Following Bliss (1997) and similar studies to this paper (e.g. Gürkaynak, Sack, and Wright (2007), Hu, Pan, and Wang (2013), or Malkhozov, Mueller, Vedolin, and Venter (2014)), I weight the price deviations by the inverse of a bond's duration. When minimizing the unweighted price errors, bonds with a longer maturity obtain a higher weighting, due to the higher degree of price sensitivity, which leads to a less accurate fit at the short end (see e.g., Ferstl and Hayden (2010)). I verify my estimation results by comparing the estimated yield curves with the estimates published by central banks and the international yield curves used in Wright (2011) and Pegoraro, Siegel, and Tiozzo 'Pezzoli' (2013).

B. *Noise Measures*

The calculation of the illiquidity measure, $illiq_t$, follows closely Hu, Pan, and Wang (2013). The illiquidity measure is constructed using the zero-coupon curve backed out from the daily cross-section of bonds and bills. For each date t, let b_t be the vector of model parameters backed out from the data, N_t is the number of securities available with maturity in a certain maturity range, and let $y^i(b_t)$ denote its model-implied yield.[7]

[6] Alternatively, one could also minimize the squared deviations between actual and model-implied yields. Since arbitrageurs are mainly interested in price deviations, however, I choose to minimize the deviations in prices.

[7] Hu, Pan, and Wang (2013) only consider bonds with a remaining time-to-maturity between 1 and 10 years. In this paper, I calculate the illiquidity measure for two different maturity ranges, one to ten years and five to 25 years. The latter maturity range is more reasonable when comparing the illiquidity measures derived from nominal and real yield curves since there are only few real bonds with a short time to maturity.

The illiquidity measure is then defined as a measure of dispersion in yields around the fitted yield curve:

$$illiq_t = \sqrt{\frac{1}{N_t}\sum_{i=1}^{N_t}[y_t^i - y^i(b_t)]^2}. \tag{4}$$

Additionally, I also apply data filters to ensure that the illiquidity measures are not driven by single observations. In particular, given the daily cross-section of bonds and their pricing errors in the yield space, I calculate the cross-sectional dispersion. Any bond with an observed (market-) yield-to-maturity more than four standard deviations away from the model implied yield is excluded from the calculation of the illiquidity measure. In practice, this is a fairly mild filter which is rarely triggered.[8]

The second noise measure is constructed according to Musto, Nini, and Schwarz (2014). It is no longer based on pricing errors in the yield space but on the difference between observed and fitted prices directly. A positive measure means that, on average, the securities used to calculate the measure are expensive relative to the smoothly fitted yield curve, i.e. the market price is on average higher than the model-implied price. Conversely, the securities are relatively cheap when the measure is negative. One potential reason for the measure to change from a negative to a positive sign could be a demand increase. Alternatively, the measure could driven by supply or a change in preferences of investors. In what follows, I will refer to this second noise measure as mispricing, m_t. As mentioned above, in contrast to the illiquidity measure, the mispricing measure can take both a negative or a positive sign since price errors are not squared before summing.

$$m_t = \frac{1}{N_t}\sum_{i=1}^{N_t}(P_t^i - P^i(b_t)) \tag{5}$$

This looks very similar to the objective function minimized when fitting the daily yield curves. Therefore, by construction, the mispricing is close to zero across all available

[8] If triggered, most of the time the filter removes just one bond on a given day. The maximum number of bonds that were removed due to this filter is four.

securities.[9] In order to ensure that the mispricing is not driven by prices of single securities, I apply a similar filter as for the illiquidity measure. Again, I calculate the cross-sectional dispersion but this time in the price space. Afterwards I exclude any bond whose observed price is more than two standard deviations away from the model implied price.

C. Nominal Bond Data

For the US there are three different categories of nominal bonds: Treasury bills, Treasury notes, and Treasury bonds. I get daily prices and issue-specific static information from the Center for Research in Security Prices (CRSP).[10] The CRSP daily Treasury file provides end-of-day quotes on all outstanding Treasury securities for the period from June 14, 1961 to the end of December 2013. An immediate issue that arises is determining the set of securities to be included in the estimation. Following the methodology of Gürkaynak, Sack, and Wright (2007), I try to only use securities that are similar in terms of their liquidity and that do not have option-like features which would affect their prices.[11] In other words, we would ideally have securities that only differ in terms of their coupons and maturities.

- Therefore, I exclude all securities with option-like features, including callable bonds and flower bonds.
- I also exclude all securities with less than one month to maturity, since the yields on these securities often behave oddly which could be triggered by the lack of liquidity for those issues.
- In contrast to Gürkaynak, Sack, and Wright (2007), I also include all Treasury bills with initial maturities of six months or one year in my sample. This helps to improve the short-term fit of the yield curve. However, one might be concerned about market segmentation between Treasury notes and bills (Duffee (1996)).

[9] It is not exactly equal to zero because prices are a non-linear function of forward rates.

[10] The data from the CRSP database was downloaded via the Wharton Research Data Services (WRDS).

[11] For example callable bonds or bonds with optional maturity dates.

- I exclude the two most recently issued securities with maturities of two,three, four, five, seven, ten, twenty, and thirty years. These are the "on-the-run" and "first off-the-run" issues that often trade at a premium to other Treasury securities, owing to their greater liquidity and their frequent specialness in the repo market (see, e.g., Barclay, Hendershott, and Kotz (2006), Goldreich, Hanke, and Nath (2005), or Fontaine and Garcia (2012)).
- Finally, other securities I exclude on an ad hoc basis. For example, I exclude the May 1995 8.5 percent five-year note which has strange prices over a period of about three years. I also drop observations with obvious pricing errors such as negative prices or negative bid ask spreads.

This data-selection process ensures that I estimate an "off-the-run" Treasury yield curve for which the liquidity of the included securities should be relatively similar. Over the full estimation period I use use price data of 3,027 securities (1,742 Treasury bills, 1,164 Treasury notes, and 121 Treasury bonds). Using the NS functional form, I estimate the Treasury yield curve over a horizon of 30 years for the period between January 1, 1987 and December 31, 2013.[12]

[Insert Tables 1 here.]

Table 1 provides details of my bond samples. Over the full sample period, I have on average 164 notes, bonds and bills to fit the US nominal yield curve. The number of securities for the U.S. varies over time, with a noticeable dip around the late 1990s and early 2000. This decrease in the number of bonds coincides with the large surpluses of the U.S. government and a reduction in the issuance of Treasury notes and bonds. Table 1 also reports other key variables used to construct the three noise measures. The average duration, maturity, and price are fairly stable over time. This alleviates the concern that the variation in the measures is driven by the time-series variation in the characteristics of the securities.

[12]Setting the horizon to 30 years is natural given that the Federal Reserve has started to regularly issue bonds with a maturity at issue of 30 years in February 1977. Choosing a longer horizon could be problematic since this would involve a lot of extrapolation on the long end of the curve.

D. TIPS Data

The data for the Treasury inflation-protected securities (TIPS) are also downloaded from CRSP. The Federal Reserve Bank started to issue TIPS on January 1, 1997. Accordingly, daily price data is available between the January 1, 1996 and the December 31, 2013. The TIPS prices are reported as real clean prices since TIPS trade on a real price basis, i.e. the principal (and, hence, the coupon payments) are not inflation-adjusted. However, settle prices will be inflation-adjusted.[13]

TIPS are indexed to inflation with a lag of three months. This indexation lag can lead to erratic security prices close to maturity. For this reason, following Gürkaynak, Sack, and Wright (2010), TIPS with less than 18 months to maturity are dropped from the estimation. This leaves me with data on 50 different TIPS. I estimate the TIPS yield curve for the period from January 7, 1999 to December 31, 2013. I only start the estimation on January 7, 1999 since this is the first day for which I have price data for five different TIPS available.

As can be seen from Table 1, on average, I have around 20 TIPS to fit the real yield curve, respectively. More importantly, also for the real bond sample the key variables used for the construction of the noise measures seem to be stable over time.

III. Empirical Results

A. Illiquidity Measure and Mispricing - Descriptives

A.1. Yield Curve Dispersion and Limits to Arbitrage

This section discusses the illiquidity measure according to Hu, Pan, and Wang (2013) both for nominal bonds and TIPS. They approximate illiquidity using the dispersion in the yield curve as discussed in section II.. The summary statistics for this measure are

[13]Example: TIPS trade on a real price basis which ensures that the prices for TIPS hoover around the par value of 100. When buying this security, however, one would have to pay the inflation-adjusted price (the price for the bond with the inflation-adjusted principal and coupon payments) which might also include inflation-adjusted accrued interest.

reported in Table 2. Both mean and standard deviation are very similar for nominal bonds and TIPS. However, the minima and maxima seem to be different for the two time series. Moreover, the mean and the standard deviation are clearly higher during the time between July 2008 and December 2009. This can also be seen from Figure 1a which plots the time series of monthly averages of the illiquidity measure for securities with residual time-to-maturity between one and ten years.

[Insert Table 2 and Figure 1 approximately here.]

The time series for nominal bonds and TIPS are clearly correlated. They share the same prominent spike in September 2008, the time when Lehman Brothers filed for chapter 11. The time period between July 2008 and January 2010 - the financial crisis - seems to be an especially illiquid period. Although by far less dramatic than the financial crisis, the burst of the dotcom bubble, on March 10, 2000, led to another period of low liquidity. This is consistent with the findings of Hu, Pan, and Wang (2013) and corresponds well to the shortages in funding capital and the associated limits to arbitrage. In general, it seems that illiquidity in TIPS is more pronounced than in nominal markets.[14] However, since TIPS with residual time-to-maturity of less than 18 months are excluded from the sample when fitting the real yield curves, a measure which only includes bonds between one and ten years might not be a good measure for a comparison of illiquidity in nominal bonds and TIPS.[15] For this reason, I choose an alternative maturity range from two to 20 years for the illiquidity measure .[16] The resulting time series are plotted in graph b) of Figure 1. Now, the correlation between real and nominal measures is even higher, especially during illiquid periods. The cross-correlations of the daily time series are reported in Table 3. They largely support what one expects from looking at Figure 1.

[14]The U.S. real bond market seems to be extremely liquid during the period before January 2002. A more plausible explanation for this, however, is limited data availability - between five and eight securities per day - which leads to a very good fit of the Nelson-Siegel model.

[15]Additionally, TIPS tend be longer lived than nominal securities. This can be witnessed from Table 1 which reports a considerably longer average duration and time-to-maturity for TIPS.

[16]Even though I estimate the yield curve over a horizon of 30 years, I don't consider maturities between 20 and 30 years since the NS model tends to have difficulty in fitting the term structure for maturities of 20 years and longer. The reason for this is that the forward rates asymptote too quickly to be able to capture the convexity effects at longer maturities.

[Insert Tables 3 approximately here.]

Panel A reports the correlations over the full periods, i.e. the longest possible periods available. The correlation coefficients between the two different measures within one bond market are about .91. The correlations between nominal bonds and TIPS lie between .69 and .79. This suggests that the two markets are equally exposed to liquidity shocks. Panel B of Table 3 reports the correlation coefficients for the time period between December 2007 and December 2010 when liquidity was low. The correlation coefficients clearly increase during this period. This is not surprising given that financial markets become more correlated during times of economic distress and that illiquidity is particularly high in such periods (see, e.g. Hameed, Kang, and Vishwanathan (2009) for equity markets and Karnaukh, Ranaldo, and Söderlind (2014) for FX markets).

Figure 2 shows the illiquidity measure for two different maturity buckets. *Short* includes bonds with residual time-to-maturity between two and eight years and *Long* includes all bonds with residual time-to-maturity between eight and 20 years.

[Insert Figure 2 approximately here.]

The co-movement of the time series suggests that liquidity shocks affect all parts of the yield curve in a similar way. Also the level of illiquidity seems to be roughly the same for short and long maturities. The only notable exception from this pattern is the high spike in short-term illiquidity present in TIPS around the default of Lehman. In this period the illiquidity measure for short maturities is more than double the measure for long maturities.

A.2. Short- vs Long-term Mispricing in Nominal Bonds and TIPS

In this subsection, I focus on the behavior of the mispricing measure discussed in section II.. The monthly time series for the measures both for short and long maturity bonds are reported in figure 3. As can be seen from 3a the mispricing in nominal bond markets follows are very peculiar pattern. While short-term bonds almost exclusively trade at a premium relative to the smooth yield curve, the opposite is the case for long-term bonds. In fact, the short- and long-term time series almost perfectly mirror each other which is confirmed by a correlation coefficient of -.80. Figure 3b shows the corresponding time series for TIPS. Here, the pattern is less obvious. However, it seems that during illiquid periods the mispricing is pretty much the opposite compared to nominal bonds. This is most obvious around 2002 and 2009 when long-term TIPS were significantly more expensive on average relative to the smooth yield curve. The correlation coefficient for TIPS is -.47.

[Insert Figures 3 and 4 approximately here.]

The striking difference in the mispricing patterns of nominal bonds and TIPS becomes more clear when one takes the difference between the long- and the short-term time series. This measure could be interpreted as the average premium at which long-term bonds (TIPS) trade compared to short-term bonds (TIPS). If mispricing is closely related to the demand schedules of market participants, then this could be called excess demand for long-term bonds over short-term bonds. The respective monthly time series are plotted in figure 4. This picture suggests that the mispricing in TIPS is very different from mispricing in nominal bonds. In fact, the correlation coefficient between the two time series is -.66. Moreover, it seems that the difference between these two markets becomes especially evident during times of economic distress and increased illiquidity. This is difference is rather surprising given that the nominal bonds and TIPS are fairly similar securities in terms of return volatility (source...) and even identical when it comes to credit risk. One obvious question to ask is what explains the mispricing in the two markets? The next subsections try to address this question in some detail for the TIPS market.

B. Explaining Mispricing on the Security Level

In this subsection I test whether mispricing in nominal bonds and TIPS on the security level can be explained by liquidity. Given the well documented fact that Treasury securities serve as a safe harbour during times of economic distress, one would expect that the mispricing of a security is associated with its liquidity. Similar to Musto, Nini, and Schwarz (2014), I collect data on proxies for liquidity that differ for each security: (1) the bid-ask spread, (2) the total dollar amount of the security outstanding, and (3) the share of the amount outstanding that is held in stripped form.

The bid-ask spreads obtained from CRSP reflect the transaction cost of a roundtrip purchase and sale of a particular security. Intuitively, larger bid-ask spreads should be associated with lower prices since the transaction costs are reflected in prices. Data for the other two liquidity proxies is hand collected from the Treasury's monthly statement of public debt which can be downloaded from http://http://www.savingsbonds.gov. Both, the amount outstanding and the share of the security that is stripped, measure the quantity of the security that is potentially available to trade. One would expect it to be easier to find a trade partner for security with a larger amount outstanding which increases the liquidity of the security. Conversely, the share of a security that is stripped into separate coupon and principal payments measures the fraction no longer available to trade. Stripping, therefore, effectively reduces the amount outstanding of a security. A large share is, hence, expected to reduce the liquidity of a Treasury security. I regress these liquidity proxies panel regressions on the mispricing measure of the individual securities $m_{i,t}$. The regressions are of the following form:

$$m_{i,t} = \alpha + \beta' L_{i,t} + \gamma * Longterm + \delta * Indexratio + \zeta_t + \epsilon_{i,t}, \tag{6}$$

where $m_{i,t}$ denotes the mispricing measure for the i^{th} security on day t, ζ_t is a day fixed-effect, *Longterm* is a dummy for securities which are included in the long maturity bucket, *Indexratio* is the indexratio for a given TIPS, and $L_{i,t}$ is the vector of the liquidity proxies.[17] The standard errors account for clustering within day t and allow for arbitrary heteroskedasticity.

The results for nominal bonds and TIPS for the financial crisis period are reported in Table 4. Panel A shows the coefficients and standard errors for nominal securities. The negative sign of the coefficient of the bid-ask spreads suggests that higher transaction

[17]The variable indexratio is obviously only available for TIPS and not for nominal bonds.

costs are associated with a liquidity discount. Moreover, the positive coefficient on total amount outstanding and the negative coefficient on the share of a security that is stripped confirm that small issues tend to be relatively cheap.

[Insert Table 4 approximately here.]

However, the liquidity proxies cannot fully explain the mispricing of long-term bonds. The coefficients of the respective dummy variable is highly significant. The negative coefficient suggests that short-term nominal bonds trade at a premium. The interaction term of the average bid-ask spread on a given day t and the total amount outstanding examines how the impact of the amount outstanding varies with overall liquidity in the Treasury market. The average bid-ask spread serves as a measure of overall liquidity. The positive coefficients indicate that during illiquid periods the demand for larger issues increases substantially relative to the demand for smaller issues.

Panel B reports the regression coefficients for TIPS. Most notably, the bid-ask spread is no longer significant and the coefficient of amount outstanding is negative. It seems that liquidity is not the reason for the relative high price of long-term TIPS. Moreover, the sign of the interaction term changed which suggests that the relative demand for smaller issues increases more during illiquid periods than the demand for large issues. The positive coefficient on the long-term dummy is consistent with Figure 3. Moreover, the reason for the very large coefficient for the share of a security that is stripped is that TIPS are rarely (almost never) stripped and if so the shares are very low.[18] Also, the negative coefficient on the indexratio dummy is consistent with the interpretation that the market attaches a positive value to the deflation options embedded in TIPS. Moreover, the more negative dummy during the crisis shows that investor attach a higher value to the deflation option during the recent financial crisis. This is consistent with the findings of Grishchenko, Vanden, and Zhang (2011).

Overall, it seems that the preference for liquidity explains the mispricing in nominal bonds but not in TIPS. This conclusion is also confirmed in regressions over other

[18]Only TIPS with an issue maturity of 30 years are stripped. The average stripped share of securities that are stripped is 0.64 percent.

subsample periods. Tables 5 and 6 show the regression results for four subsamples which roughly correspond to the period shortly after the Dotcom bubble burst, the stock market surge between 2003 and 2008, the financial crisis, and the time after the financial crisis.

[Insert Tables 5 and 6 approximately here.]

Most importantly, mispricing in TIPS is very different from mispricing in nominal bonds.[19] While the mispricing in nominal bonds seems to be well explained by liquidity, this is not the case for TIPS. If anything, the regressions for TIPS suggest that less liquid TIPS are expensive relative to the smooth yield curve. Moreover, the longterm dummy in TIPS and nominal bonds always have the opposite signs.

C. What Drives the Mispricing in TIPS?

In what follows, I will focus on the mispricing in TIPS. In particular, I will try to explain the difference of mispricing of long-term and short-term TIPS.

C.1. Liquidity Measures and Market Unrest

In this subsection, I test whether mispricing in TIPS can be explained by a series of liquidity measures. Many paper document that prices of securities can be affected by liquidity, among others, Longstaff (2009), Vayanos and Vila (1999), Huang and Wang (2010) and Amihud, Mendelson, and Pedersen (2005). To this end, I run the following regression of monthly changes in mispricing on monthly changes of the different liquidity variables.

$$\Delta m_t = \alpha + \beta' \Delta L_t + \epsilon_t \tag{7}$$

[19]The bid-ask spread is excluded from the "Dotcom"-regression of the first column in table 5. The reason for this is too little variation in the bid-ask spreads for TIPS both between securities and across time.

Where Δm_t stands for the monthly changes in mispricing, ΔL_t for monthly changes in the liquidity measures, and ϵ is an error term. I include six different variables in the analysis. *GSU* stands for the liquidity measure of short-term off-the-run Treasury bonds from Goyenko, Subrahmanyam, and Ukhov (2011). This is a direct measure of short-term liquidity in Treasury markets.[20] *Amihud* refers to the widely used illiquidity measure developed by Amihud (2002) which serves as a measure of stock market illiquidity. It uses the absolute value of the daily return-to-volume ratio to capture price impact. *TIV* is the Treasury implied volatility from Mueller, Vedolin, and Yen (2013). The *TIV* represents a model-free volatility measure from one-month options written on 30-year Treasury futures. *VIX* stands for the monthly VIX index obtained from the Chicago Board Options Exchange (CBOE). This index is commonly referred to as "fear index" and serves as an indicator for market unrest and market illiquidity. *Global Illiquidity* refers to the monthly time series of the global funding illiquidity measure from Malkhozov, Mueller, Vedolin, and Venter (2014). This measure captures global shocks to funding liquidity which limit arbitrage opportunities. Finally, *FontaineGarcia* is the illiquidity measure from Fontaine and Garcia (2012). The authors construct a funding liquidity proxy from different prices of on- and off-the-run bonds.

Table 7 reports the regression results. The first column shows a regression of mispricing on the three measures *GSU*, *Amihud*, and TIV. The negative and significant slope coefficient for *GSU* means that an increase in short-term illiquidity in Treasuries is associated with an increase in mispricing. Moreover, the weakly significant positive coefficient of *Amihud* shows that the mispricing in TIPS seems to be related to stock market illiquidity. However, this result should be taken with a grain of salt given that the coefficient is no longer significant in the final regression in the third column. The positive sign of TIV is also sensible when Treasury implied volatility is interpreted as a measure for uncertainty. The same is true for the positive and significant slope coefficient of VIX in the second column. Interestingly, the TIPS mispricing is not associated with the global illiquidity measure from Malkhozov, Mueller, Vedolin, and Venter (2014). This

[20] The measure is built upon nominal Treasury bonds and not TIPS. Therefore, the additional but plausible assumption that illiquidity of nominal bond markets is closely related to illiquidity in the TIPS market is needed in order to make a statement about the relationship of mispricing and TIPS illiquidity.

is somewhat surprising given the methodological similarities in deriving the measures. The fact that also the coefficient of $FontaineGarcia$ remains insignificant suggests that shortages in funding liquidity cannot explain the TIPS mispricing.

[Insert Tables 7 approximately here.]

Finally, the third column reports the results from regressing the mispricing on all available liquidity measures. Only the coefficient on GSU turns out to be significant. The explanatory power of the six variables is fairly low, the regression R^2 is only 0.12. Hence, the mispricing in TIPS is at best partially explained by liquidity.

C.2. Supply and Treasury market Liquidity

In this subsection, I test whether the mispricing in TIPS is related to Treasury bond and TIPS supply or Treasury-specific liquidity measures. A significant relationship between supply measures and the mispricing would question the interpretation that short- and long-term mispricing in TIPS is driven by demand shocks. I measure supply of nominal securites as the monthly gross issuance of bills, notes and bonds and the supply of TIPS as the monthly gross issuance of TIPS notes and TIPS bonds.[21] These data are obtained from webpage of the Securities Industry and Financial Markets Association (SIFMA). As discussed above, liquidity can have significant effects on the security prices. In order to approximate TIPS-specific liquidity, I use two variables. First, I use the total notional amount of repo fails experienced by primary bond dealers. A repo fail can take two forms: First, a fail occurs when a primary dealer is not able to deliver a Treasury security that the dealer had previously committed to deliver. Second, a fail occurs when the primary dealer does not receive back a Treasury security pledged as collateral on a repurchase agreement. Both failures indicate that market participants are not able to timely locate certain securities. Hence, we typically see repo fails amount increase during illiquid periods.

Second, similar to Fleckenstein, Longstaff, and Lustig (2014) I use the ratio of total TIPS

[21] In an alternative specification, I measure the supply of nominal securities as the monthly gross issuance of notes and bonds only. The regression results are qualitatively the same (not shown).

trading volume by US primary dealers to total coupon-bearing Treasury note and bond trading volume by US primary dealers as an alternative liquidity measure. Changes in this ratio capture variation in the liquidity of TIPS relative to that of Treasury bonds.[22]

[Insert Figure 5 approximately here.]

The monthly time series of repo fails and the transaction volume ratio are plotted in figure 5. Graph 5a shows that the liquidity of TIPS relative to Treasury bonds has increased over time but stagnated or even decreased during the recent financial crisis. This is consistent with D'Amico, Kim, and Wei (2010), Pflueger and Viceira (2011) and Whelan (2014) who find that TIPS have become more liquid relative to nominal bonds over time. The data on repo fails and transaction volumes are obtained from the Primary Dealer Survey which is carried out by the Federal Reserve Bank of New York.

[Insert Table 8 approximately here.]

Panel A of table 8 report the results of regressions of monthly changes in mispricing on the discussed supply and liquidity measures. The slope coefficients in the different regression specifications are all insignificant. Moreover, the R^2 in the four regressions are very low. The signs of the coefficients for the supply and the transaction volume ratio are consistent with the corresponding regression specification in Fleckenstein, Longstaff, and Lustig (2014).

C.3. Stock-Bond and Stock-TIPS Covariance

Another possible explanation for the difference in short- and long-term mispricing between nominal bonds and TIPS could be related to hedging demand. When deciding on their portfolio allocation, risk averse investors take into account the covariance between stocks and nominal bonds and TIPS, respectively. Risk averse agents with an exposure in the stock market also in assets featuring low covariance with the stock market. This

[22]Fleming and Krishnan (2009) note that transaction volumes are good proxies of TIPS liquidity.

hedging demand is particularly strong for assets whose returns negatively covary with stock returns. Campnbell and Cartea, Saul, and Toro (2012) find substantial negative betas for both nominal Treasury bonds and TIPS. An increase in excess demand for long-term TIPS, i.e. the difference in mispricing, could therefore be rationalized by an increase in the spread between the covariance of stocks with long- and short-term TIPS. In order to test this hypothesis I estimate a dynamic conditional correlation model for stock and short- and long-term TIPS returns. The returns on stocks are approximated by daily returns on the S&P 500 index. The daily returns for TIPS are calculated using the daily TIPS yield curve estimates by Gürkaynak, Sack, and Wright (2010). I use the daily dataset to calculate the returns on a five and 14 years constant-maturity bond. Then, I use these returns to estimate the short- and long-term stock-TIPS covariance.

[Insert Figure 6 and Table 8 approximately here.]

The resulting monthly time series are plotted in figure 6a. The covariance is negative during almost the entire sample period. There are three prominent negative spikes in both conditional covariances. The timing of the first two spikes seems to match the periods of high TIPS mispricing fairly well. This becomes more clear in figure 6b which plots the difference of long- and short-term stock-TIPS covariance and the TIPS mispricing, i.e. *excess covariance*. Apart from the negative spike around 2011, excess covariance almost mirrors excess demand. This is underlined by a correlation coefficient of -.49 and a negative and significant regression coefficient in a regression of changes in excess demand on changes in excess covariance (see panel B of table 8). Overall, it seems that hedging demand has some explanatory power for the mispricing in TIPS.
In order to explain the difference in mispricing between nominal bond and TIPS, however, the corresponding covariances of stock and nominal bond returns should be such that excess covariance for nominal bonds is positive.[23]

[Insert Figure 7 approximately here.]

[23] I calculate the covariance of stock and nominal bond returns analogously to TIPS. To calculate the returns on nominal constant-maturity bonds I rely on the dataset provided by Gürkaynak, Sack, and Wright (2007).

Figure 7 shows graphs similar to figure 6 but for nominal bonds. It is obvious that the patterns of short- and long-term covariances are very similar for TIPS and nominal bonds. Also, the excess covariance measure for nominal bonds is not consistent with the hedging demand explanation from above. Hence, under plausible assumptions hedging demand is cannot be the driver for mispricing in nominal bonds.

C.4. Shocks to the Term-Structure of Expected Inflation

In this subsection, I examine whether shocks to expected inflation help to explain changes in TIPS mispricing. Expected inflation is a natural variable to look at since inflation-indexing is the only difference between nominal bonds and TIPS in terms of security design. Hence, one would expect that the term structure of inflation expectations affects the pricing of TIPS.

One difficulty is that inflation expectations are not observable directly. I use two different sources to measure inflation expectations. First, I use data from the surveys of consumers of the University of Michigan. The Michigan survey is conducted monthly and asks households to estimate the expected price change over the next twelve months and over the next five years. I use both the one- and the five-year expected inflation in my analysis. I use the Michigan survey instead of other popular surveys such as the Livingston survey or the survey of professional forecasters (SPF) for several reasons. First, the Livinston survey is conducted only twice a year and the SPF data is available only quarterly. Carrying out my analysis for such low frequencies would lead to a substantial in information. Moreover, in their paper Ang, Beckaert, and Wei (2007) argue that among the three survey candidates the Michigan survey is closest to be economically unbiased.

Second, I use data on the term structure of expected inflation provided by Haubrich, Pennacchi, and Ritchken (2012) on the webpage of the Federal Reserve Bank of Cleveland. They develop a model of nominal and real bond yield curves that has seven factors. The model is estimated using nominal Treasury yields, survey inflation forecasts, and inflation swap rates. The resulting term structure of expected inflation is available on a monthly basis. In my analysis, I include the expected inflation over horizons of five and 14 years.[24]

[Insert Table 9 approximately here.]

Table 9 reports the results from a regression of monthly changes in mispricing on monthly changes in expected inflation. The first and the second columns show the results for the Michigan survey data. *MichiganSlope* is simply the difference between the long and the short horizon expected inflation. The regression coefficients are all insignificant. [25] However, the signs of the regression coefficients are nevertheless educative.[26] This can be seen most easily from the positive sign of the slope coefficient in the second column. All else equal, a negative shock to short-term expected inflation leads to an increase in the slope of the term structure of expected inflation. The positive sign of the coefficient in the second column therefore suggests that an increase in the slope leads to an increase in the excess demand for long-term TIPS. This is confirmed by the strongly significant slope coefficients for expected inflation measured according to Haubrich, Pennacchi, and Ritchken (2012). This findings are consistent with Barr and Campbell (1997) who report that real rates and expected inflation are strongly negatively correlated at short horizons, but no at long horizons. The last column of the table includes slope of the term structure of inflation expectation both for the Michigan survey and Haubrich, Pennacchi, and Ritchken (2012).[27]

One possible explanation for this finding could be the fact that short-term TIPS are close to perfect substitutes to nominal bonds whenever expected short-term inflation is close to zero. In this case, investors with preferences for liquidity would rationally opt for nominal bonds instead of TIPS.

[24] I use these maturities since five and 14 years are the average maturities of the short and long-maturity buckets. However, the results remain unchanged even if I vary the these horizons.

[25] One possible reason for the lack of significance could be that both measures of expected inflation from the Michigan survey have relatively short horizons.

[26] Multicollinearity should not be a problem in the regressions in columns one and three since the correlations between short- and long-term expected inflation are for both datasets around .5. In any case, in what follows I will focus on the slope of the term structure of expected inflation as an explanatory variable which is free of any multicollinearity.

[27] Multicollinearity is not a problem in this regression, the correlation between the two slopes of expected inflation is .13

D. Predicting the Mispricing in TIPS

In this section, I will test whether the difference between short- and long-term mispricing in TIPS is predictable. From Figure 4 one can see that this difference is relatively persistent. Theoretical work by Mitchell, Pedersen, and Pulvino (2007) ,Duffie (2010), Gromb and Vayanos (2002), Ashcraft, Garleanu, and Pedersen (2010), Brunnermeier and Pedersen (2009), and others stresses that slow-moving capital may explain the persistence and arbitrage opportunities. An implication of the slow-moving-capital explanation is that mispricing in the market should be predictable by changes in the amount of capital invested in financial markets. With an increasing amount of capital invested, some of this capital flows into the mispriced markets and consequently leads to a reduction in mispricing.

First, to test the slow-moving-capital hypothesis I run similar regressions as Fleckenstein, Longstaff, and Lustig (2014). I regress monthly changes in TIPS mispricing on lagged excess returns on the value-weighted CRSP index and lagged excess returns on a portfolio of U.S. Treasury nominal bonds with time-to-maturity between five and ten years. [28] The regression results are reported in panel A of Table 10.

[Insert Table 10 approximately here.]

The first column reports the slope coefficients for the entire sample while the second, third, and fourth column report the results for the aforementioned subsamples. The negative relations between TIPS mispricing and prior returns are consistent with the slow-moving-capital hypothesis. In particular, an increase in the wealth of stock or bond investors leads to a future decrease in mispricing. From the subsample analysis it becomes evident that this inverse relation of capital and mispricing was non-existing during the years from 2003 to 2008 but particularly strong during the recent financial crisis.

[28]The excess returns on the value-weighted CRSP index were downloaded from Ken French's website. The bond portfolio returns are downloaded from CRSP Treasury monthly.

Second, I further examine the relationship between TIPS mispricing and the slope of the term-structure of expected inflation. As shown in previous section, expected inflation explains the mispricing partly. In the regressions of panel B of Table 10, I test whether the slope of expected inflation predicts the mispricing. Again, I report results for the entire sample and the usual subsamples. The first column shows that the slope of expected inflation predicts the mispricing. This is true both for Michigan survey data and for data obtained from Haubrich, Pennacchi, and Ritchken (2012). The positive sign of the regression coefficients means that an increase in the slope leads to a future increase of the difference between long- and short-term mispricing. This is intuitive given that an increase in the slope of expected inflation can be either caused by a negative shock to short-term expected inflation or a positive shock to long-term inflation. In both scenarios, one would expect the demand differential between long- and short-term TIPS to change accordingly. Interestingly, this relationship only holds during times of low liquidity. During the "Boom" subsample the relationship is insignificant or even negative. Insignificance could be explained by investors which are less desperate for liquid assets during periods with high overall liquidity. In this case, investors would not opt for more liquid nominal bonds even if expected short-term inflation is close to zero.

E. Return Predictability

Above I argued that TIPS mispricing can potentially be rationalized by investors with a preference for liquid assets. In fact, I theorize that negative shocks to expected short-term inflation paired with illiquid periods lead short-term TIPS investors to opt for more liquid nominal bonds. This, potentially, is a valuable reallocation even for investors that are concerned about inflation given that short-term nominal bonds and TIPS become close to perfect substitutes when short-term expected inflation is close to zero or even slightly negative. In this scenario, the decrease in demand for short-term TIPS leads to an increase in TIPS mispricing. Moreover, one would expect that the TIPS mispricing has some predictive power for future short-term excess returns in TIPS. An increase in TIPS mispricing is expected to negatively predict short-term excess returns in TIPS during illiquid periods with low short-term expeceted inflation.

Table 11 reports the results from regressions of differences in TIPS excess returns on lagged differences in TIPS mispricing.

[Insert Table 11 approximately here.]

I run the regression both for short- and long-term TIPS excess returns. The quarterly excess returns are calculated following Pflueger and Viceira (2011) and Whelan (2014). The monthly sampling frequency of the excess returns lead to overlaps which are accounted for by adjusting the standard errors according to Hansen and Hodrick (1983) using 3 lags. The first row reports the results for short-term TIPS excess returns. It turns out that TIPS mispricing negatively predicts short-term excess returns during the recent crisis. This is in line with the reasoning from above. Even though the coefficient is insignificant for the subsample including the Dotcom crisis, it carries a negative sign. Interestingly, the slope coefficient is positive during the "Boom" subsample is positive. A possible explanation for this could be investors which are not concerned about increased illiquidity of their asset holdings during overall very liquid periods. Finally, the second row of table 11 reports the regression results for long-term TIPS excess returns for which TIPS mispricing has no predictive power. This is not surprising if TIPS mispricing is mostly driven by changes in demand for short-term instead of long-term securities.

IV. Robustness of the Results

In this section, I conduct various robustness tests of the results presented earlier. First, I show that the results are robust to alternative definitions of the maturity buckets. So far, short-term bonds were defined as bonds with a residual time-to-maturity between two and eight years whereas long-term bonds have time-to-maturities from eight to 20 years. I relax this assumption and calculate the illiquidity and mispricing measures for two alternative specifications: $short7$ ($long7$) includes bonds with time-to-maturities between two and seven (seven and 20) years and $short10$ ($long10$) includes bonds with time-to-maturities between two and ten (ten and 20) years. Figure 8 plots the illiquidity measures for the three alternative specifications. The time series for nominal bonds in

8a are very similar for the three different cases. There is some disagreement early in the sample period but from 2007 onwards the three time series are essentially identical. 8b shows the illiquidity measures for TIPS. Here, the co-movement of the time series is even more striking. The short- and long-term illiquidity is essentially identical for the three different specifications.

[Insert Figure 8 approximately here.]

Figure 9a plots the relevant mispricing time series as the difference of long- and short-term mispricing for nominal bonds and 9b shows the corresponding time series for TIPS. Again, the results do not vary much across the different maturity specifications. The correlation coefficients between the measures for nominal bonds and TIPS are -.51 (*short*7, *long*7 specification), -.55 (*short*10, *long*10 specification), and -.66 (*short*, *long* (original) specification).

[Insert Figure 9 approximately here.]

Moreover, the results of the security-level and explanatory regressions remain qualitatively unchanged for the different specifications (not shown).

Another potential concern could be that the difference in mispricing between short- and long-term bonds stems from local differences in the fit along the yield curve. In other words, the mispricing measure for different parts of the yield curve, e.g. different maturity buckets, could be driven by the local fit of the yield curve. In order to alleviate such concerns, I construct a second mispricing measure, adj_m_t, which takes into account the local fit of the yield curve:

$$adj\_m_t = \frac{\frac{1}{N_t}\sum_{i=1}^{N_t}(P_t^i - P^i(b_t))}{\frac{1}{N_t}\sum_{i=1}^{N_t}|P_t^i - P^i(b_t)|} \quad (8)$$

The adjusted measure is simply equal to m_t divided by the absolute pricing error across all securities within a certain maturity bucket. Consequently, it takes values between

-1 and 1. A value of 1 (-1) indicates that all observed security prices are higher (lower) than the prices derived from the fitted yield curve.

Figure 10 plots the resulting adjusted mispricing measures for nominal bonds and TIPS. These measures are calculated as the difference between the adjusted mispricing measures for long- and short-term bonds.

[Insert Figure 10 approximately here.]

The correlation between the two measures is -.43 which is slightly lower than for the unadjusted measures. However, graph in figure 10 underlines the main finding of this paper: the short- and long-term within-market mispricing for TIPS is very different from nominal bonds. In fact, the findings of this paper suggest that there is a fairly strong negative relationship between the two.

V. Conclusion

This paper explores the information contained in the dispersion of the nominal and real yield curve. Examining squared pricing errors in the yield space and average pricing errors in the price space delivers new stylized facts about available arbitrage capital and mispricing in TIPS. The main findings of the paper can be summarized as follows:

1. The nominal and real yield curve dispersion look almost identical. Moreover, the dispersion for short- and long-term securities is highly correlated both for nominal bonds and TIPS. This suggests that arbitrage capital is efficiently allocated across markets and also along the yield curve.

2. The short- and long-term mispricing in nominal bonds and TIPS is very different. In fact, difference between long- and short-term mispricing in nominal bonds almost perfectly mirrors the one in TIPS (correlation coefficient of -.66). This analysis suggests that the marginal TIPS-investor is fundamentally different from the marginal Treasury bond investor.

3. An analysis of the pricing errors reveals that mispricing in nominal bonds is well explained by a flight-to-liquidity behavior of investors. This is not true for TIPS.
4. An increase in TIPS mispricing can be explained by an increase in short-term liquidity of nominal Treasury bonds and a steepening of the slope of the term structure of inflation expectations. Moreover, the slope predicts the TIPS mispricing. This finding could be rationalized with investors who opt for the more liquid nominal bonds whenever the short-term expected inflation is very low, i.e. short-term nominal bonds and short-term TIPS are close to perfect substitutes.
5. Finally, I find evidence for the slow-moving capital hypothesis. Lagged stock and bond excess returns predict the TIPS mispricing.

TIPS is a relatively new asset class for which not much research has been conducted yet. This paper shows that, despite institutional similarities, TIPS are very different from nominal Treasury bonds. In future research, it would be interesting to more closely investigate the investor base of TIPS. Improving our understanding of TIPS could potentially help to employ these securities more efficiently both from a policy but also from an investors' perspective.

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VI. Tables

Table 1
Bond Data Summary Statistics

The numbers reported are the time-series averages of the daily cross-sectional means. The number of bonds reported in the second column is the number of bonds used to fit the yield curve. "Maturity" refers to the average residual time-to-maturity. Age measures the time elapsed since the the issue date of the security and duration refers to the Macaulay duration.

Sample Period	# Bonds	Coupon (%)	Maturity	Age	Duration	Price	Yield (%)
Panel A: US Nominal Bonds, 1987 - 2013							
1987-2013	164	6.36	6.05	5.01	4.12	108.25	4.65
1991-1995	174	7.74	5.67	4.06	3.59	107.52	5.76
1996-2000	168	6.86	6.10	4.90	3.90	106.35	5.73
2001-2005	111	6.00	7.45	6.57	4.99	111.76	3.56
2006-2013	191	4.03	5.85	5.39	4.49	109.30	2.31
Panel B: US Real Bonds, 1999 - 2013							
1999-2013	19	2.78	11.17	3.56	8.93	108.08	1.77
2001-2005	11	3.39	12.29	3.24	9.40	109.60	2.20
2006-2013	27	2.18	9.93	4.22	8.52	109.72	0.97

Table 2
Illiquidity Measure Summary Statistics

Panels A and B report summary statistics (mean, median, standard deviation, maximum, and minimum) for the illiquidity measure in basis points. The table reports numbers for two different maturity ranges. *1to10* includes all securities with a residual time-to-maturity between one and ten years and *all* includes all securities with a residual time-to-maturity between two and 20 years. Data is daily and runs for each measure for the full sample (maximum time period available) and for the period between July 2008 and December 2009.

Convention	Sample Period	Mean	Median	Std	Max	Min
Panel A: US Nominal Bonds, 1987 - 2013						
1to10	1987-2013	5.03	4.57	2.77	28.93	1.12
1to10	2008-2009	10.58	7.78	6.81	28.93	1.16
all	1987-2013	5.01	4.34	3.17	32.75	1.11
all	2008-2009	12.46	9.59	8.54	32.75	1.11
Panel B: US Real Bonds, 1999 - 2013						
1to10	1999-2013	4.74	3.57	5.10	51.83	0.11
1to10	2008-2009	13.12	9.87	10.87	51.83	1.15
all	1999-2013	3.73	3.24	3.20	29.80	0.11
all	2008-2009	9.55	6.83	6.48	29.80	1.11

Table 3
Correlations between Illiquidity Measures

The table reports the correlation coefficients between the different illiquidity measures. The correlation coefficients are calculated using the daily time series of the different measures. *1to10* refers to the illiquidity measure based on securities with time-to-maturity between one and ten years and *all* refers to a maturity range from five to 25 years, respectively.

	Nominal		Real	
	1to10	all	1to10	all
Panel A: Full Periods				
1to10	1	0.91	0.69	0.72
all		1	0.75	0.79
1to10			1	0.95
all				1
Panel B: Crisis Period - July 2008 - December 2009				
1to10	1	0.99	0.90	0.89
all		1	0.88	0.89
1to10			1	0.95
all				1

Table 4
Mispricing during the Financial Crisis

This table presents panel regressions of mispricing on several security characteristics for the period from July 1, 2008 to December 31, 2009. Panel A shows results for nominal U.S. sovereign debt securities. Panel B shows results for TIPS. Day fixed effects are included in each regression. The t-statistics (in parentheses) account for clustering within day t and arbitrary heteroskedasticity. *** indicates significance at the 1% level, ** at the 5% level, and * at the 10% level.

Panel A: Nominal Securities							
$Bid - Ask_{i,t}$	-10.24***						-3.02***
	(-7.91)						(-6.89)
$ln(total_{i,t})$		0.77***					1.42***
		(31.45)					(4.80)
$Share - Stripped_{i,t}$			-3.08***				-1.76***
			(-43.18)				(-33.30)
$Bid - Ask_{avg,t} * ln(total_{i,t})$				17.94***			-23.34***
				(31.36)			(-3.35)
$Longterm$					-0.78***		-0.22***
					(-42.19)		(-19.11)
$Indexratio$						NA	NA
R-Squared	0.03	0.19	0.31	0.24	0.17		0.37
Observations	37,745	35,439	35,439	35,439	37,745		35,439
Panel B: TIPS							
$Bid - Ask_{i,t}$	1.34***						1.38***
	(3.87)						(5.03)
$ln(total_{i,t})$		-1.29***					-1.02***
		(-36.24)					(-9.18)
$Share - Stripped_{i,t}$			-191.29***				53.97***
			(-37.45)				(7.20)
$Bid - Ask_{avg,t} * ln(total_{i,t})$				-22.40***			2.95
				(-26.11)			(1.28)
$Longterm$					0.18***		0.01
					(12.17)		(1.01)
$Indexratio$						-6.05***	-5.08***
						(-34.05)	(-28.51)
R-Squared	0.01	0.19	0.03	0.17	0.01	0.27	0.35
Observations	8,780	8,780	8,780	8,780	8,780	8,780	8,780

Table 5
TIPS Mispricing and Liquidity Measures

This table presents panel regressions of TIPS mispricing on several security characteristics for the periods between January 1, 2001 and December 31, 2013. The sample period is divided into four subperiods which capture specific economic environments: Dotcom Bubble contains the data from January 1, 2001 to July 1, 2003; Boom from July 1, 2003 to July 1, 2008; Crisis from July 1, 2008 to January 1, 2010; After Crisis from January 1, 2010 to December 31, 2013. Day fixed effects are included in each regression. Standard errors (in parentheses) account for clustering within day t and arbitrary heteroskedasticity. *** indicates significance at the 1% level, ** at the 5% level, and * at the 10% level.

	Dotcom	Boom	Crisis	After Crisis
$Indexratio$	2.04***	-0.57***	-5.08***	-2.14***
	(14.52)	(-12.56)	(-28.51)	(-54.17)
$Bid - Ask_{i,t}$	NA	-0.09	1.38***	-0.03
		(0.33)	(5.03)	(-0.65)
$ln(total_{i,t})$	-0.03**	-2.77*	-1.02***	-0.30***
	(-2.27)	(1.86)	(-9.18)	(-12.69)
$Share - Stripped_{i,t}$	5.26***	1.76	53.97***	-68.51***
	(6.48)	(1.50)	(7.20)	(-41.00)
$Bid - Ask_{avg,t} * ln(total_{i,t})$	NA	41.67*	2.95	0.58***
		(23.89)	(1.28)	(3.35)
$Long - term$	0.35***	-0.20***	0.01	0.04***
	(22.69)	(-53.63)	(1.01)	(5.64)
R-Squared	0.23	0.21	0.35	0.42
Observations	3,671	17,335	8,780	25,619

Table 6
Nominal Bonds Mispricing and Liquidity Measures

This table presents panel regressions of nominal bond mispricing on several security characteristics for the periods between January 1, 2001 and December 31, 2013. The sample period is divided into four subperiods which capture specific economic environments: Dotcom Bubble contains the data from January 1, 2001 to July 1, 2003; Boom from July 1, 2003 to July 1, 2008; Crisis from July 1, 2008 to January 1, 2010; After Crisis from January 1, 2010 to December 31, 2013. Day fixed effects are included in each regression. Standard errors (in parentheses) account for clustering within day t and arbitrary heteroskedasticity. *** indicates significance at the 1% level, ** at the 5% level, and * at the 10% level.

	Dotcom	Boom	Crisis	After Crisis
$Indexratio$	NA	NA	NA	NA
$Bid-Ask_{i,t}$	-35.46***	-17.43***	-3.02***	0.77***
	(-90.97)	(-97.96)	(-6.89)	(12.56)
$ln(total_{i,t})$	0.77***	0.87***	1.42***	0.18***
	(8.70)	(13.83)	(4.80)	(10.91)
$Share-Stripped_{i,t}$	-0.45***	-0.24***	-1.76***	-0.49***
	(-84.13)	(-18.72)	(-33.30)	(-34.95)
$Bid-Ask_{avg,t} * ln(total_{i,t})$	-18.49***	-20.65***	-23.34***	-2.03***
	(-8.95)	(-13.82)	(-3.35)	(-4.91)
$Long-term$	-0.88***	0.35***	-0.22***	-0.26***
	(76.01)	(47.40)	(-19.11)	(-82.19)
R-Squared	0.58	0.49	0.37	0.39
Observations	29,927	88,523	35,439	141,349

Table 7
TIPS mispricing and Liquidity

This table reports regressions of monthly changes in TIPS mispricing (long - short) on different liquidity proxies. *GSU* refers to short-term liquidity in Treasury bonds, *Amihud* measures the overall stock market illiquidity, *TIV* is the Treasury implied volatility, *VIX* refers to the VIX index, *Global Illiquidity* measures global funding liquidity, and *FontaineGarcia* stands for a measure of funding liquidity in US Treasuries. The t-statistics reported in parentheses are adjusted according to Newey and West (1987). *** indicates significance at the 1% level, ** at the 5% level, and * at the 10% level.

	Liquidity Measures		
GSU	-0.57***		-0.54***
	(-2.33)		(-2.56)
Amihud	0.05*		0.01
	(1.75)		(0.44)
TIV	0.04		0.03
	(1.11)		(0.099)
VIX		0.29**	0.13
		(2.21)	(0.62)
GlobalIlliquidity		0.05	0.04
		(1.24)	(1.19)
FontaineGarcia		0.02	0.02
		(1.20)	(1.29)
R-Squared	0.10	0.05	0.12

Table 8
TIPS mispricing and Supply, Liquidity and Hedging Demand

This table reports regressions of monthly changes in in TIPS mispricing (long - short) on supply measures and Treasury market liquidity measures. Supply is measured by the gross issuance (in billions USD) both of Treasury bonds and TIPS. *VolRatio* equals the ratio between monthly transaction volumes of TIPS divided by Treasury bonds. *RepoFails* measures the monthly total notional amount (in billions USD) of repo fails experienced by primary dealers. Finally, *ExCov* stands for the difference between stock-long-term TIPS and stock-short-term TIPS covariance. The t-statistics reported in parentheses are adjusted according to Newey and West (1987). *** indicates significance at the 1% level, ** at the 5% level, and * at the 10% level.

Panel A: Supply, Volume, and Repo Fails					
$TreasuryIssuance$	-0.19			-0.20	
		(-1.09)		(-0.93)	
$TIPSIssuance$	-1.08			-2.21	
	(-0.86)			(-1.51)	
$VolRatio$		1.27		4.13	
		(0.97)		(1.29)	
$Repofails$			-2.37	-1.93	
			(-1.08)	(-0.88)	
R-Squared	0.04	0.00	0.00	0.06	
Panel B:Hedging Demand					
ExCOV					-0.38*
					(-1.73)
R-Squared					0.10

Table 9
Mispricing in TIPS and Expected Inflation

This table reports regressions of monthly changes in the TIPS mispricing (long - short) on measures of expected inflation for different horizons. *Michigan* refers to data on expected inflation from the Michigan survey, *HBR* refers to data on expected inflation obtained from Haubrich, Pennacchi, and Ritchken (2012). The t-statistics reported in parentheses are adjusted according to Newey and West (1987). *** indicates significance at the 1% level, ** at the 5% level, and * at the 10% level.

	Expected Inflation Measures				
MichiganShort	-5.19				
	(-1.04)				
MichiganLong	1.77				
	(0.33)				
MichiganSlope		4.71			3.91
		(1.24)			(1.17)
HBRShort			-56.09**		
			(-2.26)		
HBRLong			55.17**		
			(1.98)		
HBRSlope				56.99***	52.74***
				(2.51)	(2.82)
R-Squared	0.03	0.08	0.04	0.08	0.10

Table 10
Return Predictability

The first row presents predictive regressions of changes in TIPS mispricing on lagged excess stock and bond returns and on the slope of the term structure of expected inflation for the period between January 1, 1999 and December 31, 2013. Columns two, three, and four report results from subsample regressions: Dotcom contains data from January 1, 1999 until July 1, 2003; Boom from July 1, 2003 until July 1, 2008; Crisis from July 1, 2008 until January 1, 2010; After Crisis from January 1, 2010 until December 31, 2013. The t-statistics reported in parentheses are corrected using the Hansen and Hodrick (1983) GMM correction with 3 Newey-West lags. *** indicates significance at the 1% level, ** at the 5% level, and * at the 10% level.

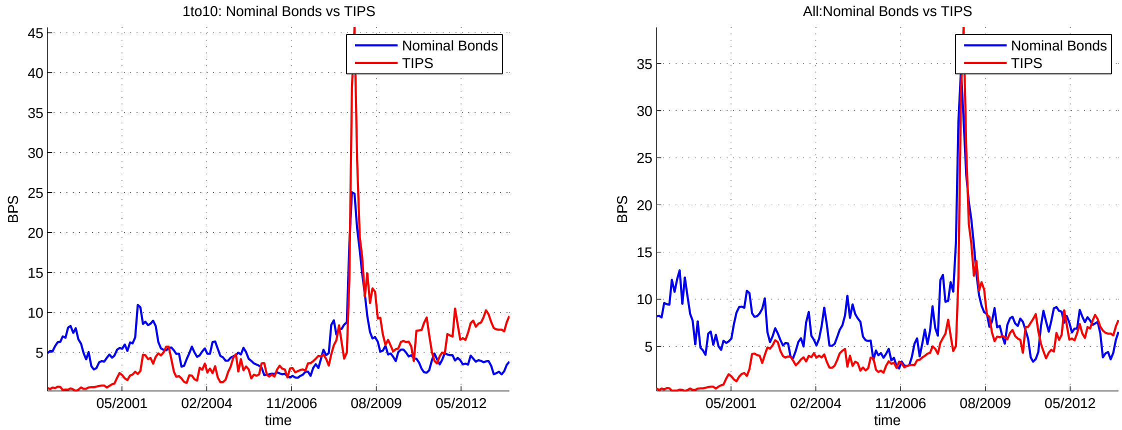
Panel A: Slow-moving capital				
	Entire Sample	Dotcom	Boom	Crisis
$Stock_{t-1}$	-0.69*	-0.35	-0.14	-1.08**
	(-1.92)	(-1.21)	(-0.41)	(-1.98)
$Stock_{t-2}$	-0.66**	0.42	-0.31	-1.10***
	(-2.00)	(1.45)	(-1.12)	(-2.48)
$Bond_{t-1}$	-0.30	-1.62***	0.55	-0.10
	(-0.58)	(-2.55)	(0.71)	(-0.15)
$Bond_{t-2}$	-0.29	0.99	-0.03	-0.52
	(-0.67)	(1.49)	(-0.04)	(-0.92)
R-Squared	0.14	0.18	0.04	0.28
Panel B: Expected Inflation				
	Entire Sample	Dotcom	Boom	Crisis
$MichiganSlope_{t-1}$	7.19**	9.91***	-5.45***	13.23**
	(2.30)	(3.33)	(-4.17)	(2.27)
R-Squared	0.08	0.15	0.19	0.13
$HBRSlope_{t-1}$	42.59*	85.33***	-8.07	84.43*
	(1.81)	(3.11)	(-0.38)	(1.81)
R-Squared	0.07	0.32	0.01	0.08

Table 11
Return Predictability

The first row presents predictive regressions of changes in 3-month real excess returns on changes in TIPS mispricing for the period between January 1, 1999 and December 31, 2013. Columns two, three, and four report results from subsample regressions: Dotcom contains data from January 1, 1999 until July 1, 2003; Boom from July 1, 2003 until July 1, 2008; Crisis from July 1, 2008 until January 1, 2010; After Crisis from January 1, 2010 until December 31, 2013. The t-statistics reported in parentheses are corrected using the Hansen and Hodrick (1983) GMM correction with 3 Newey-West lags. *** indicates significance at the 1% level, ** at the 5% level, and * at the 10% level.

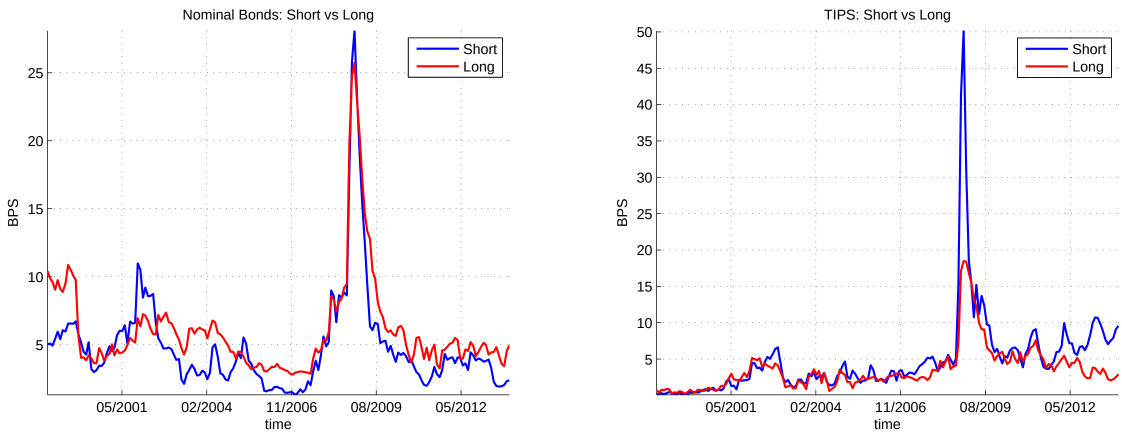
	Entire Sample	Dotcom	Boom	Crisis
$Retx5y$	-0.04	-0.62	4.45	-1.19**
	(-0.03)	(-0.19)	(0.88)	(-2.27)
R-Squared	0.00	0.00	0.02	0.01
$Retx15y$	-0.01	-1.99	11.18	-2.80
	(-0.03)	(-0.24)	(1.13)	(-1.60)
R-Squared	0.00	0.01	0.04	0.01

VII. Figures



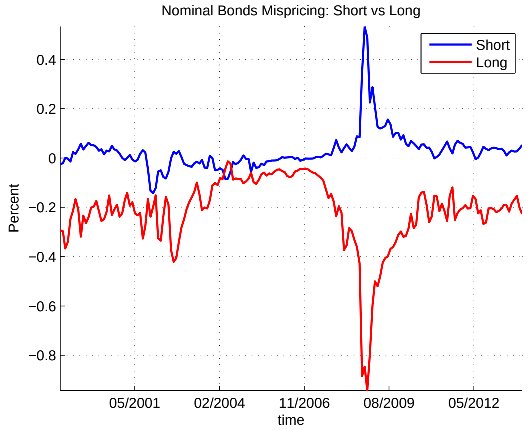
(a) 1 to 10 years (b) 2 to 20 years

Figure 1. Dispersion in the yield curve measured according to Hu, Pan, and Wang (2013), both for nominal bonds and for TIPS. The left graph shows the time series for the the original measure in their paper which includes only bonds with a residual time-to-maturity between one and ten years, the measure in the right graph includes securities with a residual time-to-maturity between two and 20 years.

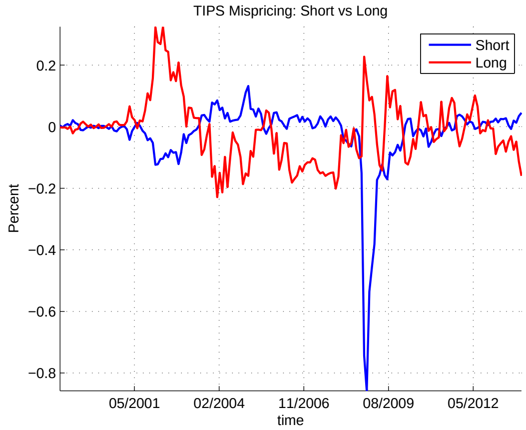


(a) Short- and long-term nominal bonds (b) Short- and long-term TIPS

Figure 2. Illiquidity measures both for short- and long-term nominal bonds and TIPS, respectively. Short includes all bonds (TIPS) with residual time-to-maturity between 2 and 8 years, long includes bonds (TIPS) with residual time-to-maturity between 8 and 20 years.



(a) Short- and long-term nominal bonds



(b) Short- and long-term TIPS

Figure 3. Mispricing both for short- and long-term maturity nominal bonds and TIPS, respectively. Short includes bonds with time-to-maturity between 2 and 8 years, long includes bonds with time-to-maturity between 8 and 20 years.

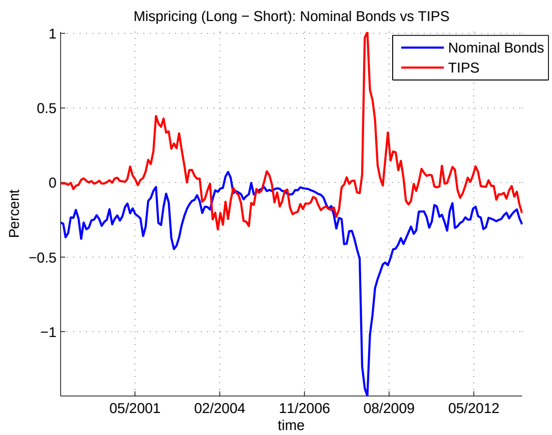
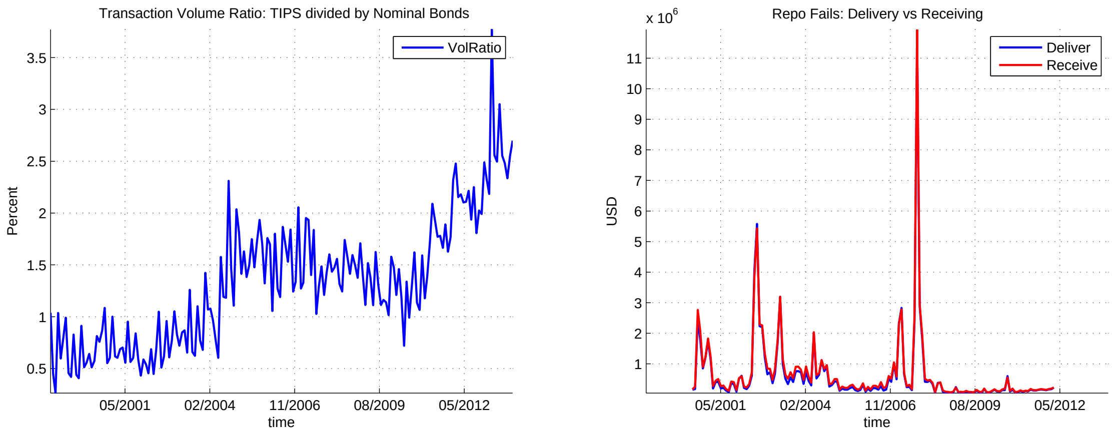


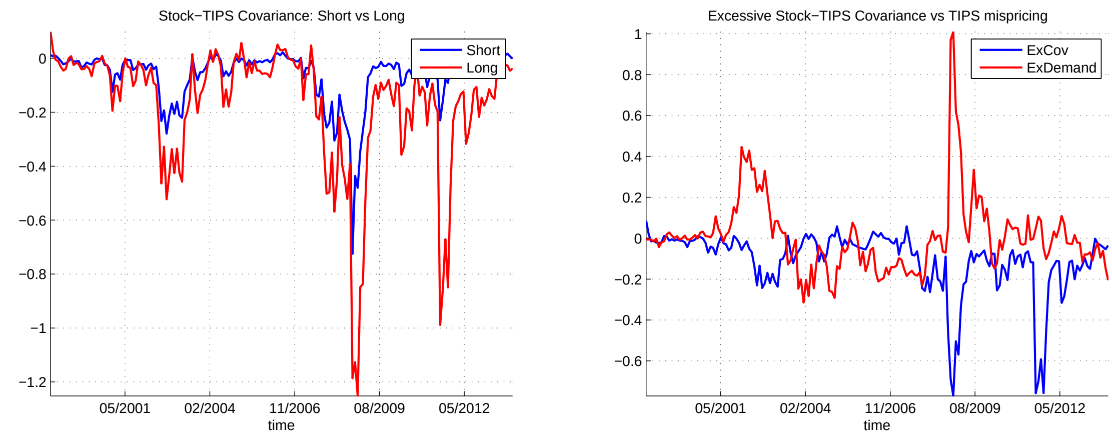
Figure 4. Monthly mispricing defined as the difference of mispricing in long- and short-term bonds (TIPS), i.e. long - short.



(a) Transaction Volume Ratio

(b) Repo Fails

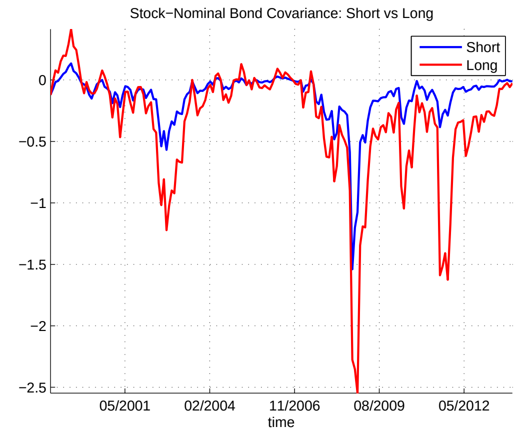
Figure 5. Transaction Volume Ratio is equal to the average weekly transaction volume in nominal bonds as reported by primary dealers divided by corresponding volume in TIPS. The total monthly notional amount in repo fails in USD terms both for receiving and delivery.



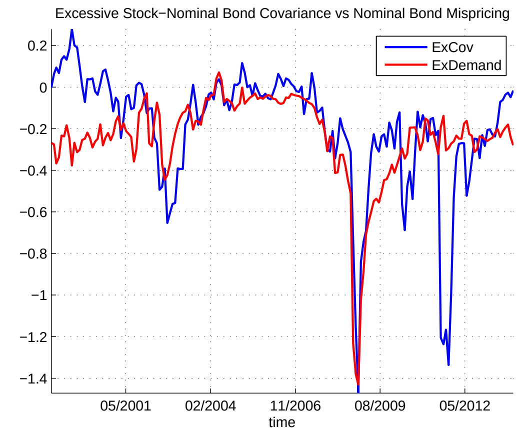
(a) Stock-TIPS Covariance: Short vs Long

(b) Excess Covariance vs Excess Demand

Figure 6. The left figure plots the stock-TIPS covariance for short- (5 years) and long-term (14 years) TIPS. The excess Covariance is equal to the difference between stock-TIPS covariance long and stock-TIPS covariance short. Excess demand corresponds to the difference between long- and short-term TIPS mispricing.

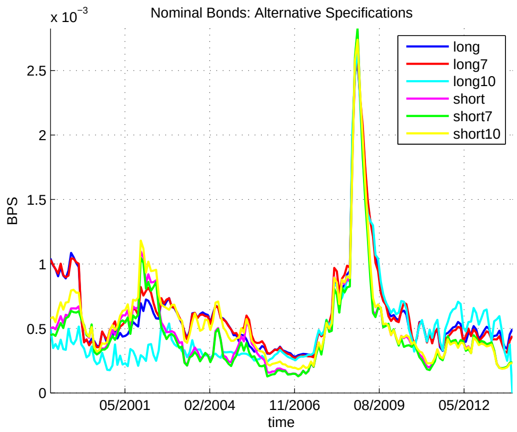


(a) Stock-Bond Covariance: Short vs Long

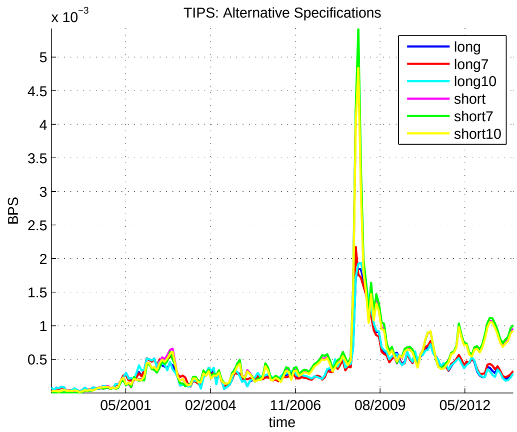


(b) Excess Covariance vs Excess Demand

Figure 7. The left figure plots the stock-bond covariance for short- (5 years) and long-term (14 years) nominal bonds. The excess Covariance is equal to the difference between stock-bond covariance long and stock-bond covariance short. Excess demand corresponds to the difference between long- and short-term nominal bond mispricing.

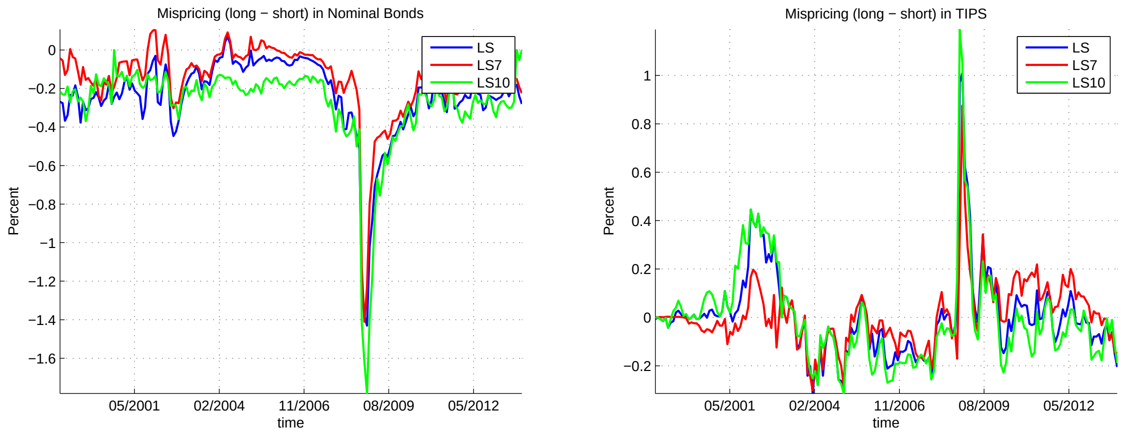


(a) Illiquidity in Nominal Bonds



(b) Illiquidity in TIPS

Figure 8. The figures plot the illiquidity measures for the alternative specifications of the short- and long-term maturity bonds. The left figure reports the monthly measures for nominal bonds and the right figure for TIPS.



(a) Mispricing in Nominal Bonds

(b) Mispricing in TIPS

Figure 9. The figures plot the mispricing (long - short) measures for the alternative specifications of the short- and long-term maturity bonds. The left figure reports the monthly measures for nominal bonds and the right figure for TIPS.

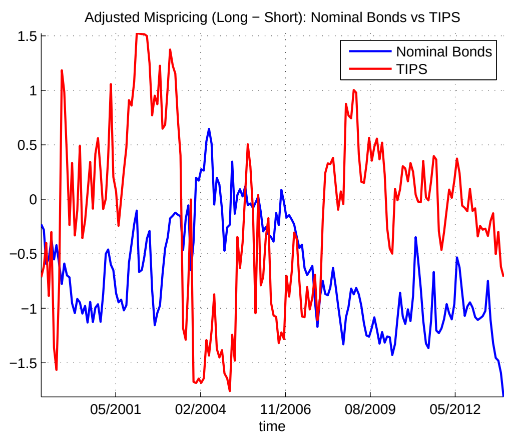


Figure 10. Monthly adjusted mispricing defined as the difference of long- and short-term bonds, i.e. long - short. The correlation coefficient of the two time series is -.43.