Notes on Bonds: Liquidity at all Costs in the Great Recession

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Abstract: We address the connection between market stress and asset pricing by analyzing a large and systematic discrepancy arising among off-the-run U.S. Treasury securities during the crisis. We begin by showing that bonds traded for much less than notes with identical maturity and coupon. The gap exceeded five percent in December 2008. We then ask how the small differences between these securities, in particular their liquidity, could project to such a large gap in prices. We gauge the potential for bond-note arbitrage in two ways. First, with data on repurchase rates and fails, we highlight the frictions arbitrageurs encountered in funding a short position in the notes. Second, with daily transactions data on trades by insurance companies, who are large buy-and-hold fixed income investors, we relate demand for the expensive but liquid note to the cross section of insurers' characteristics.

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Notes on Bonds: Liquidity at all Costs in the Great Recession

Abstract: We address the connection between market stress and asset pricing by analyzing a large and systematic discrepancy arising among off-the-run U.S. Treasury securities during the crisis. We begin by showing that bonds traded for much less than notes with identical maturity and coupon, with the gap exceeding five percent in December 2008. We then ask how the small differences between these securities, in particular their liquidity, could project to such a large gap in prices. We gauge the potential for bond-note arbitrage in two ways. First, with data on repurchase rates and fails, we highlight the frictions arbitrageurs encountered in funding a short position in the notes. Second, with daily transactions data on trades by insurance companies, who are large buy-and-hold fixed income investors, we relate demand for the expensive but liquid note to the cross section of insurers' characteristics.

Price disparities among Treasury securities are rare, but when observed, they are a valuable opportunity to learn about market forces other than beliefs about future cash flows. There is an accordingly robust literature on such disparities, for example the Old Bond/New Bond trade (e.g. Krishnamurthy 2002). In this paper we address an exceptionally large disparity among off-the-run Treasuries, which has not previously been documented, and which we will call the bond-note trade. Bonds, we show, traded cheap relative to notes with the same maturity date and with cash flows matched exactly via STRIPs, during the recent financial crisis. The price disparity exceeded $5 per $100 face value at the peak in December 2008. What makes the bond-note trade fruitful for study is not just the size of the arbitrage opportunity and its clean identification, but also the availability of rich data on the cross section of buyers and sellers. Specifically, we see all Treasury security transactions by U.S. registered insurance companies throughout the crisis, and we also see the changing circumstances of these insurers. We do not claim that insurers are the marginal investor in Treasuries nor that they are the most likely arbitrageurs of Treasury mispricings. In fact, we are not motivated to understand the actions of insurers as a whole, but rather to understand the characteristics of an investor group that are correlated with a propensity to either exploit or exacerbate a mispricing. There is a rich cross section of characteristics across the set of U.S. insurers as is certainly the case with any other type of Treasury market participant. Thus, we have a unique opportunity to learn about the motives that underlie taking one side of the trade versus the other by relating the transactions to the cross-sectional characteristics of these insurers. Our results can give policymakers, who rely on close pricing relationships among comparable securities for efficient transmission of policy changes, important insight into the particular types of stresses that may lead mispricings to worsen.

The typical bond-note trade compares two securities issued 20 years apart: a bond issued as a 30-year in the 1980s, and a note issued as a 10-year in the 2000s. From the perspective of a potential buyer in 2007 - 2009, there are two salient differences between the securities: coupon and liquidity. The U.S. has been in a declining interest rate environment since the late 1970s, sobonds issued in the 1980s have higher coupons and trade at a higher premium relative to par, while notes are more liquid. The higher liquidity of the notes may reflect the larger issue sizes, the newer vintage, or some path dependent effect of events since the 1980s that sorted the bonds into certain portfolios, such as the amount of stripping that occurs (e.g. Jordan, Jorgensen and Kuipers, 2000). But whatever the cause, notes trade at lower bid-ask spreads and the frequency of note transactions in our insurance sample is much higher relative to that of bonds. We focus on the difference in liquidity, rather than coupon, for two reasons. First, despite numerous discussions with practitioners about tax and accounting considerations, we cannot identify an economic rationale for a high-coupon discount. Second, there is an economic rationale for an illiquidity discount, particularly during this period of extreme stress. We thus use our data on insurers' Treasury transactions to see whether insurer characteristics that are likely to relate to their preference for liquidity can help to explain which insurers demand the expensive and liquid note rather than the bond.

Besides the underlying demand promoting the note over the bond, we also analyze the barriers to the bond-note arbitrage trade. Considering the magnitude of the disparity, these barriers presumably would need to be quite high. The net funding costs to establishing this trade, as in Krishnamurthy (2002), are a logical candidate, so we assemble a database of special repo transactions of the relevant notes. What is most noticeable in these data is not the direct cost to establishing the bond-note arbitrage – in fact, the funding costs implied by the special repo rates turns out to be quite low – but rather that, in the crisis period, particularly at the peak of the disparity during the fourth quarter of 2008, repo market liquidity largely dried up. This could represent a friction in the repo market that prevented the *supply* of securities lent from meeting the demand for borrowing securities. When interest rates are low and special repo rates cannot go below zero[1], potential suppliers of securities for shorting become unwilling to lend, particularly at a time when counterparty risk is high. The sharp decline in specials repo transactions could also represent a lack of *demand* for arbitrage capital. Only a short seller would agree to receive a relatively low specials rate to lend cash against a particular security. Exploiting any Treasury pricing anomaly requires borrowing the relatively expensive security to deliver it into a short sale.

The apparent mispricing of Treasury securities is consistent with the perspective of the "limits to arbitrage" literature. Funding and transactions costs did not erase the profits available from trading against the mispricing, and we show that the magnitude of the discrepancy provided a clear arbitrage opportunity from the perspective of a hold-to-maturity investor. The "limits to arbitrage" literature presents an explanation for why an arbitrageur may still shy away from such a trade. The essence of the story - described in detail in papers such as Shleifer and Vishny (1998), Gromb and Vayanos (2002) and Vayanos and Vila (2009) - is that arbitrageurs are risk-averse and have a short-horizon or are capital constrained. Each of these frictions can prevent an arbitrageur from taking the perspective of a hold-to-maturity investor, making the mispricing less attractive. In particular, as noise traders move prices for reasons unrelated to an asset's fundamentals, arbitrageurs are tempted to trade the security to take advantage of the mispricing. However, arbitrageurs have to assume the risk that the noise traders could make the mispricing

[1] Prior to the spring of 2009, there was no explicit penalty for failing to deliver a security in a repo transaction, which effectively put a lower bound of zero on repo rates.

worse in the short-run, which subjects the arbitrageur to interim losses. Because the arbitrageur is risk-averse in the short-run and has limited capital, this risk can deter the arbitrageur from acting. This is true even if the mispricing would make the arbitrageur a sure profit, if he/she could hold out indefinitely.

The Treasury market is an ideal setting to cleanly establish the existence of an arbitrage and test some empirical implications. Treasury securities all share identical credit risk and do not differ in priority, while some securities are more easily traded than others. Bonds are cheaper than notes, perhaps because some investors have a preference for the greater liquidity of notes, but arbitrage capital is normally available to keep the prices of notes and bonds aligned. The crisis was a time in which the spread between note and bond yields skyrocketed, in part due to a withdrawal of arbitrage capital. Treasury market anomalies (not confined to the bond-note spread) during the crisis are discussed in these terms by Hu, Pan and Wang (2010). Furthermore, by identifying specifically which Treasury securities are relatively cheap and which are relatively expensive, we can investigate the *types* of participants that are either exploiting the arbitrage or acting as noise traders based on their trading activity in these particular Treasury securities at the time that the pricing divergence widened. What we find is that long-horizon investors, precisely those for whom the bond-note trade is truly an arbitrage, are more likely to exploit the mispricing. Also, we find that highly levered investors, those who may be desperate for liquidity at all costs, tend to exacerbate the mispricing by buying the more liquid notes as they become most expensive.

In addition to the on-the-run/off-the-run spread that is studied extensively in Krishnamurthy (2002), other anomalies in the Treasury market have also been documented. Amihud and Mendelson (1991) and Kamara (1994) compare bills and notes with less than six months remaining to an identical maturity date, so that both are effectively zero-coupon securities. During their sample, the notes were consistently cheaper (traded at higher yields) than the bills. Amihud and Mendelson argue that the price differential represents a premium for the greater liquidity of bills, but Kamara (1994) suggests that the difference owes in part to the differential tax treatment that existed at the time. In the paper most closely related to ours, Strebulaev (2003) compares the yields of coupon securities with different original-issue tenors but with identical maturity dates. He finds no evidence of systematic pricing differences within Treasury notes, although he confirms that bills tend to be more expensive than similar notes. Streubulaev finds that standard liquidity proxies are not correlated with bill-note pricing differences, thus concluding that liquidity differences are not the source of the note-bill anomaly. Another Treasury market anomaly in the TIPS market that worsened notably during the crisis was documented by Fleckstein, Longstaff, and Lustig (2010).

The plan for the remainder of this paper is as follows. In section 2, we describe the bond-note pricing anomaly and the convergence strategy that is the focus of this paper. Section 3 relates pricing anomalies in the crisis to characteristics of individual coupon securities, arguing that the cross-section of yields can be accounted for in terms of liquidity differences. Section 4 evaluates the characteristics of investors that were exploiting the arbitrage opportunity, and those that were making it worse. Section 5 concludes.

II. The Bond-note Arbitrage

In this section, we describe how we construct two portfolios with identical cash flows and show that, in normal times, the two portfolios have very similar prices. We then document the pricing anomaly that emerges and show that funding costs did not reach levels that would overwhelm the arbitrage profits.

II.1 Identical Cash Flows, Differing Prices

An example of the bond-note pricing anomaly that we explore is shown in Figure 1. The figure shows the spread between the yields to maturity on two Treasury securities, both maturing on February 15, 2015. We take the difference between an original-issue 30-year bond and an original-issue 10-year note. The bond was originally issued in 1985 with a coupon of 11.25 percent, and the note was originally issued in 2005 with a coupon of 4 percent. Throughout 2005, 2006, and much of 2007, the bond has a slightly higher yield-to-maturity than the note, by a few basis points, on average. In late 2007 and early 2008, however, the bond yield climbed substantially relative to the note yield. The difference spiked in the fall of 2008 to peak at 80 basis points, representing a price difference of about five dollars per 100 dollars face value. It is worth noting that both securities were well off-the-run during the time when the yield spread widened most notably; the bond was about 23 years off the run while the note was about 3 years off the run.

This yield spread documented in Figure 1 does not necessarily represent an arbitrage opportunity, since the note has a lower coupon than the bond and thus a longer duration. But with an upward sloping yield curve, as was the case during 2008, the difference in coupons should result in a relatively *higher* yield to maturity for the note relative to the bond; Figure 1 shows that the note has a lower yield to maturity.

To account for the difference in coupon and to conduct a precise comparison between the pricing of the note and the bond, we create a synthetic portfolio of the bond and a Treasury

STRIP to exactly match the cash flows of the note.[2] Specifically, for a note with coupon rate C_n and a bond with coupon rate C_b (both maturing on the same day), we form a portfolio that puts weight C_n / C_b on the bond and weight $1 - C_n / C_b$ in a bond principal STRIP that shares the same maturity date as the bond. The bond and note price data are obtained from CRSP, and the STRIP price data are obtained from Bloomberg. This portfolio will have identical cash flows to the note, which lets us compare the prices of two assets that generate identical cash flows. In our empirical analysis below, we show that the difference between the price of the note and that of the combined bond/STRIP portfolio is usually close to zero but grew significantly during the period of the financial crisis before returning to a narrow spread in late 2009. During the crisis, a trading strategy that bet on convergence in prices of these two portfolios would have made positive profits. Moreover, these profits would have been riskless, as long as the positions could be held until maturity, and as long as funding costs or other frictions in implementing the trade did not exceed the difference in returns on the portfolio. In principle, the net costs of funding the arbitrage could wipe out any profits created by convergence in the cash prices of the Treasury securities, although we show below that this is not the case in a very low interest rate environment without an explicit Treasury security fails penalty. In the absence of such significant frictions, this bond-note strategy could be scaled to produce enormous profits, at least for a patient investor.

In this paper we consider nine bond-note pairs similar to the example displayed in Figure 1. In all cases, the original-issue note becomes expensive relative to the portfolio comprised of

[2] Coupon STRIPS that share a maturity date are fungible whereas principal STRIPS are not, and so principal STRIPS may inherit some of the pricing anomalies of the underlying security. There is a larger price differential between the note principal and corresponding maturity coupon STRIPS than the bond principal and corresponding maturity coupon STRIPS. For this reason, we use coupon STRIPS where available and bond principal STRIPS otherwise.

the original-issue bond and STRIP with identical maturity dates, although the size of the pricing gap varies somewhat across the pairs. We explicitly incorporate the cost of forming the short position in the note using repo rates that account for any specialness in shorting a particular security. We interpret any remaining difference as potential arbitrage profits that would be available to a hold-to-maturity investment position.

II.2 Matched Maturity Bond-Note Pairs

We construct pairs of securities that share identical maturity dates, where each pair matches a Treasury security originally issued with 10 years to maturity with a Treasury security originally issued with 30 years to maturity. We consider only nominal, non-callable Treasury securities, of which the February 2015 securities (described above) are an example. Prior to 1985, the U.S. Treasury Department exclusively issued callable thirty-year securities, so we use only bonds issued after 1984. We also restrict our sample to notes that were issued prior to the summer of 2008, so that all of the bond-note pairs exist during the peak of the financial crisis. With these restrictions, we are left with nine bond-note Treasury pairs with identical maturity dates ranging from February 2015 to May 2018. Some features of these bond-note pairs are summarized in Table 1.

For each pair, we construct a portfolio that is short the note, long a fraction of the bond to match the coupons of the note, and long a Treasury STRIP to match the principal payment at maturity (as discussed above). This portfolio is constructed to have zero cash flows after origination, so it should neither have any cost nor benefit at origination. We view any money received at origination as an arbitrage opportunity. The difference between the price of the bond/STRIP portfolio and the price of the corresponding matched-maturity note is what we refer to as the "pricing error."

II.3 Funding Costs

In the classic "convergence trade" that we describe above, an arbitrageur would take a long position in the cheap security (the bond) and a short position in the expensive one (the note). In reality, it is often expensive to short some securities, a friction discussed by Duffie (1996) and Krishnamurthy (2002), among others. The only way to take a short position in a Treasury issue is to enter into a repo contract where one lends out cash and takes the security as collateral. The lender can then deliver the collateral into a short sale agreement, betting that the security price will fall, intending to buy it back at a later date and at a cheaper price. An investor wishing to bet on an anomaly in the Treasury market must short the expensive security in this way. At the same time, the investor can buy the cheap security, using it as collateral to borrow money to finance the purchase. In most repo transactions, any Treasury security is considered to be acceptable collateral, and the corresponding interest rate on the loan is known as the general collateral (GC) interest rate.

Particularly expensive issues will of course not be delivered in GC agreements, as these "in-demand" securities can be "repoed out" to raise funds at lower interest rates. When one security is unusually expensive, demand from investors wishing to short it can drive down the repo rate on that security to a level below the GC rate. That security is referred to as "special." Special repo agreements specify the precise issue that must be used as collateral and must be returned at the end of the repo contract. Securities that are expensive in the cash market are typically special in the repo market, meaning that the cost of shorting them is particularly high as the security's special repo rate will be lower than the GC repo rate. An investor betting on an anomaly in the Treasury market will receive a lower interest rate on his/her loan of cash (collateralized by the expensive security) than he/she must pay to fund the purchase of the cheap security, which will be at the GC repo rate.

The spread between GC repo and specials rate, the net funding cost to this convergence trade, could in principle wipe out the trade's profitability. Indeed, Krishnamurthy (2002) shows that the profits on the convergence trade between on-the-run and off-the-run bonds are roughly wiped out by the gap between the corresponding repo rates. Although the spread between these two bonds systematically converges over time, the average profits of this trade are close to zero due to the cost of shorting the newly issued bond. Krishnamurthy argues therefore that there is no genuine arbitrage opportunity in the old bond/new bond trade in the sample period he considers.

Besides the spread between GC and specials rates, it is important to remember that funding became quite difficult during the crisis. Strains in the repo market likely made it difficult to short comparatively expensive Treasury securities. An institutional feature of the Treasury repo market made investors reluctant to lend out their securities when GC rates became very low, as they did following Lehman's bankruptcy. Specifically, the lack of a penalty for failing to deliver on a repo transaction created a lower bound of zero on the specials rate, which could have prevented the market from clearing without excess demand or supply. [3]

[3] A market participant will lend funds against a security that is priced "special" only to meet an obligation to deliver that security. Until May 2009, the penalty for a failure to deliver a security into a transaction was that the security was to be delivered the next day at the same price. This is equivalent to giving the buyer of the security an interest free loan. Failing would thus be preferable to borrowing at a negative specials rate. So specials rates normally do not go below zero. Due to massive fails in the repo market, and a coincident drop in securities lent via repos, the Treasury Market Practices Group (TMPG), a self-governing industry group, proposed a penalty fails rate, which was backed by the Federal Reserve. The explicit penalty in failing to deliver a security was introduced in May 2009 as

Using data on repo transactions from a large interdealer broker, we show that the costs of funding the bond-note trade we propose would have been a tiny fraction of the profits from the cash market position. Figure 2 plots the monthly return on the bond-note trade (ignoring funding costs) along with the level of the GC-special rate spread (the funding cost) for the bond-note pair maturing on February 15, 2015. Although funding costs do rise during the crisis, the picture shows that the pricing differences were substantially larger than the funding costs. Even at the peak divergence in prices of the underlying securities, the repo funding costs remain below 15 basis points per month. Monthly returns, however, are much larger, in some cases exceeding 2 percent at the peak. Per $1000 principal, funding costs reach a maximum of $1 per month. Raw returns peak at $14.1 per $1000 principal in December 2008, following Lehman's bankruptcy filing in September 2008.

III. Apparent Treasury Pricing Anomalies

In this section, we explore the relationship between observed variables and the relative pricing differential of comparable Treasury securities. We begin by addressing the question of which securities became relatively cheap during the crisis and which were relatively expensive and find that there is a systematic pattern in the relative price deviations. Then we explore the time series variation in the price differential between the bond-note pairs that we consider.

III.1 Cheap versus Expensive Securities

Max (3-FFT, 0), where FFT is the base of the Federal Reserve's target rate. In a zero policy rate environment, this rule levies a 3 percent penalty rate on a fail.

The period between August 2007 and May 2009 represented a period of extraordinary market turmoil, roiling even the benchmark Treasury market. Hu, Pan, and Wang (2010) document that deviations in Treasury yields from a smooth yield curve hit a record high in the weeks following the Chapter 11 filing of Lehman Brothers in September 2008. They construct a measure of illiquidity based on the average deviation of Treasury prices from those based on a smooth yield curve and show that this measure provides a useful proxy for illiquidity and is a priced risk factor. We find that deviations from the smooth curve were not just large, but systematic: original-issue 30-year bonds became cheap relative to original-issue 10-year notes. The systematic nature of the pricing deviations motivates the bond-note pairs that we introduced in the previous section. These bond-note pairs allow us to precisely identify arbitrage opportunities, which are not necessarily represented by just any pricing deviations relative to the curve.

We start by comparing actual Treasury prices with those implied from a parametric zero-coupon yield curve fitted to the set of all coupon securities. We use the parameter estimates provided by the Federal Reserve Board, who every day fit the six-parameter model of instantaneous forward rates of Svensson (1994) to observed prices on coupon treasury securities.[4] With the parameter estimates, we can compute the fitted price of each security on every calendar day and compute the difference between observed prices and the fitted price. We denote the difference as the fitting error, which by construction has a mean close to zero across all securities.[5] We use the CRSP daily Treasury database for our Treasury security prices.

[4] See Gürkaynak, Sack, and Wright (2006) for a discussion of the methodology. See the following website for the data: http://www.federalreserve.gov/pubs/feds/2006/200628/200628abs.html

[5] The mean is not exactly zero because prices are a non-linear function of forward rates.

Figure 2 shows the average fitting error for all securities which were originally issued as thirty-year bonds, ten-year notes and five-year notes. Prior to the summer of 2007, average fitting errors were close to zero, and there was very little difference between thirty-year bonds and ten-year notes. Beginning in the fall of 2007 and extending through early summer of 2009, a notable pattern emerges. The thirty-year bonds became cheap relative to the smooth curve, and the ten-year notes became expensive. Meanwhile, the fitting errors on the five-year notes do not show systematic time series deviations. As we will show next, part of the pattern can be explained by observable liquidity proxies, but there will still remain a significant pattern that thirty-year bonds became cheap relative to ten-year notes.

To explore the determinants of the fitting error in more detail, we estimate a panel regression of the fitting errors on individual securities onto a variety of security characteristics. The regression is of the form

$$e_{it} = \alpha + \beta' X_i + \varepsilon_{it},$$

where e_{it} denotes the fitting error for the ith security on day t, and X_i is a vector of bond-specific characteristics. We use two sets of independent variables. First, as two proxies for liquidity, we include the size of the issue and the quoted bid-ask spread. We measure size as the log of the original amount of the bond issued, and use the log of the dollar value of the bid-ask spread.[6] Second, we include dummy variables indicating whether the security was originally issued as a thirty-year bond, a ten-year note, or a five-year note, with the excluded category including seven-year, three-year, and two-year notes. The regression includes observations

[6] We will eventually account for buybacks and re-openings by allowing the amount outstanding to vary by day. Another liquidity proxy could be the amount of a security that is held in stripped form versus as an entire security. 30-year bonds tend to be stripped with much greater frequency than notes, which could account for a significant share of their illiquidity.

during 2005 through 2010 and includes all coupon securities with remaining time to maturity of at least one year and no more than ten years. We also run the regression on a sub-sample of observations during the crisis period, which we define as lasting from the fourth quarter of 2007 through the second quarter of 2009. Since the same security appears many times in the sample, Newey-West standard errors are used to account for potential serial correlation in the error term.

The results are shown in Table 2. The coefficient on the amount issued is positive, suggesting that larger issues tend to be relatively expensive. This indicates that differences in liquidity, as proxied by issue size and bid-ask spreads, lead to systematic differences in pricing, with less liquid issues trading cheaper than more liquid issues. Interestingly, the effect of issue size is much stronger during the crisis, suggesting that liquidity differences were exacerbated during the crisis. Even after controlling for liquidity proxies, the dummy variables for the original-issue term of the security confirm that ten-year notes became expensive relative to thirty-year bonds. The difference in estimated coefficients on the thirty-year bonds and the ten-year notes is large and statistically significantly different from zero in both samples. During the crisis, the difference in coefficients exceeds 1, meaning that, on average over the seven quarters, bonds were more than 1 percent cheaper than notes, even after controlling for the difference in their issue sizes and bid-ask spreads.

We do not have a compelling reason why the notes became rich relative to the bonds (even after controlling for our measures of liquidity), but we conjecture that unobserved differences in liquidity are the underlying source, which were exacerbated during the crisis. The fact that more bonds are stripped (Jordan, Jorgensen and Kuipers, 2000) far more than notes may be part of the explanation. Although an interesting area for future research, the underlying reason is unimportant for our subsequent analysis. At maturity of the bond-note trading strategy, both securities are equally liquid, so from the perspective of a hold-to-maturity investor, any liquidity differences do not matter. What matters for us is that bonds systematically cheapened relative to notes, prior to maturity, which creates the potential arbitrage that we explore.

III.2 Time Series Pattern of Arbitrage

We next explore the time periods when the bond-note arbitrage grew to its widest levels, focusing on aggregate liquidity and limits to arbitrage. We conjecture that the risk aversion of potential arbitrageurs increased and arbitrage capital was withdrawn from the market. If so, the pricing error should be correlated with other systemic liquidity indicators.

To investigate this further, we run a daily time-series regression of the average pricing error across our nine bond-note pairs on several measures of aggregate liquidity. We consider the frequency of specials repo market transactions, the LIBOR-OIS spread, the volume of Treasury fails, and the repo bid-ask spread.[7] The frequency of specials market repo transactions proxies for demand of arbitrageurs. In order to establish the bond-note trade, a potential arbitrageur would need to short the note and borrow it in a specials repo transaction to deliver into the short sale. A short sale delivery is the only reason that a market participant would lend cash against a security that is trading special, as the cash lent against a particular security would earn a lower rate than in a transaction where any type of Treasury collateral is accepted. Thus, the incidence of specials transactions reflects the incidence of potential arbitrage transactions relating to these particular securities. The LIBOR-OIS spread is a proxy for liquidity and funding strains faced by potential arbitrageurs. The level of fails represents strains in the repo

[7] Fails are computed as the average dollar volume of Treasury fails to deliver and Treasury fails to receive. These include fails associated with outright cash and lending transactions. The repo bid-ask spread is computed as the difference between overnight Treasury GC repo and reverse repo rates. The 1-month LIBOR-OIS spread is used, and similar results are obtained with 3- and 6-month LIBOR-OIS spreads. The LIBOR-OIS and repo bid-ask data are obtained from Bloomberg, the Treasury fails data are obtained from the Federal Reserve, and the frequency of specials transactions are from a large interdealer broker.

market associated with a 0 lower bound on rates when the overall level of rates is very low. The repo bid-ask spread will identify transactions costs in funding markets, which would be a consideration to an arbitrageur above and beyond funding costs in the Treasury cash market. In fact, in the fall of 2009 at the height of the crisis, the repo bid-ask spread became similar in magnitude to the actual funding costs for the bond-note trade.

A plot of the monthly frequency of Treasury specials transactions and the monthly dollar volume of Treasury fails is shown in Figure 4. The frequency of specials transactions drops sharply in 2008, suggesting a drop in demand to exploit Treasury market mispricing. The largest spike in fails occurred in the fall of 2008, as the fed funds target rate was cut from 2 percent to a range between 0 and 0.25 percent, bringing other short term rates to very low levels and thus compressing the potential spread between GC repo rates and specials rates. The GC – specials spread reflects the maximum possible opportunity cost that a market participant faces in failing to deliver into a Treasury trade. Without an explicit fails penalty, and with the GC – specials spread close to zero, there was little incentive for a security borrower to agree to a negative specials repo rate.

The regression results are shown in Table 3. To account for the significant serial correlation in the pricing errors, we use Newey-West standard errors with a lag-length of 30. The results suggest that the pricing error is significantly correlated with the measures of aggregate liquidity and arbitrageur demand. The coefficient estimates are significant and show the economically intuitive sign in each of the univariate regressions, as seen in the first four columns of Table 3. The incidence of specials repo trading is significantly negative, which represents a diminished demand for arbitrage capital. The coefficient on the LIBOR-OIS spread is large and positive, indicating that broader funding strains were correlated with the anomaly in the Treasury market. The level of fails is significantly negative. This corroborates the notion that a lower GC spread makes lending expensive securities in the repo market less attractive in the presence of a zero bound on the specials rate. The high level of fails at very low specials rates may cause lenders to withdraw from the market thus reducing the availability of securities, which in turn prevents arbitrageurs from bringing prices back into line. Finally, the coefficient on the repo bid-ask spread is also positive, suggesting that the strains in the repo market also happened coincidentally with the pricing anomalies.

The results of the multivariate regression are shown in the far right column of Table 3. The coefficient estimates on the frequency of specials rates and the LIBOR-OIS spread are both significant, even after controlling for repo market transactions costs and other repo market frictions that could have affected the supply of notes lent, suggesting a paring of arbitrage demand was the predominant force in allowing the pricing error to widen as much as it did. The interpretation of these results in the context of the limits to arbitrage literature suggests that risk averse, capital constrained arbitrageurs may have withdrawn against the backdrop of high losses that the bond-note strategy would have experienced in September and October 2008, which underscored the need to hold the bond-note trade for a lengthy period to ensure a profit.

IV. Investor Response?

The pricing of Treasury securities in the crisis represented an arbitrage opportunity if the position could be held to maturity. Based on the "limits to arbitrage" paradigm, we suggest that this reflects a lack of arbitrage capital willing to take short-run risk to wait for the long-run gain. In this section, we explore the trading behavior of insurance companies, who are potential long-term investors that could profit from the bond-note trade.

IV.1 Trading and Holdings Data

We have a transactions-level dataset showing all buys and sells of Treasury securities for all U.S.-registered insurance companies. Insurers report such transactions in Schedule D within their statutory regulatory filings. The transactions data are obtained from eMAXX. For each transaction, we know the insurance company conducting the trade, along with the date, size, and direction. We combine the transactions data with regulatory accounting data from the insurers, which provides us with several measures of the insurers' financial strength and liquidity. We also construct three additional variables based on the trading history of each insurer. In sum, we consider eight cross-sectional characteristics of each insurer:

(i) *Buy-and-hold indicator*. A dummy equal to one if the insurer does not conduct any sell transaction of Treasury securities in our entire 10-year sample period.

(ii) *Horizon*. The average number of days that an insurer holds a given Treasury security.

(iii) *Churn*. The ratio of total transactions volume relative to total holdings of all Treasury securities. A lower value corresponds to a less active trader.

(iv) *Assets*. The total balance-sheet assets held by the insurer.

(v) *Annuity*. A dummy equal to one if the insurer deals substantially in the annuity business, as oppose to the life insurance or property-casualty business. During the crisis, particularly the latter half of 2008, annuity-providers suffered unusually large losses due to their exposure to equity markets and liquidity demands due to policy surrenders.

(vi) *EBITDA*. The operating earnings of the insurer, which includes gains or losses on underwriting and earnings on invested assets.

(vii) *Capital-to-Asset Ratio*. The ratio of policyholder surplus to total assets. This is a measure of leverage of each insurer.

(viii) *RBC*. The ratio of actual capital to risk based capital, where risk-based capital is regulatory measure of required capital based on the risk of the insurer's asset and liability portfolio. A higher measure indicates a better capitalized insurer.

IV.2 Regression Results

For each insurer *i* in month *t*, we construct the net purchases of notes, or bonds, or the difference between these two and denote any one of these net purchases as $NP_{i,t}$. These are natural indicators of the propensity to engage in the arbitrage trade, which we then relate to the magnitude of the bond-note pricing error and the cross-sectional characteristics of each insurer. In particular, we conduct regressions of the form:

$$NP_{i,t} = \alpha_i + \beta_i PE_t + \varepsilon_{i,t} \tag{1}$$

for net purchases of notes, bonds, and bonds minus notes. We further assume that the intercept and slope coefficients in these regression are linear functions of the characteristics of the insurer, collected in a vector X_i:

$$\alpha_i = a + b' X_i, \quad \beta_i = c + d' X_i \tag{2}$$

Substituting (2) into (1) gives:

$$NP_{i,t} = a + b' X_i + cPE_t + d' X_i PE_t + \varepsilon_{i,t} \tag{3}$$

which we then estimate as a pooled regression. The main object of interest is the coefficient on the interaction term, denoted d. This coefficient tells us whether a particular characteristic of an insurer makes the insurer more or less likely to buy the note *when it becomes particularly expensive*, such as in the fall of 2008. A positive coefficient on net purchases of bonds minus notes is consistent with exploitation of the bond-note trade. A positive coefficient on net purchases of notes alone suggests a particular demand for notes such that they are bought when most expensive. A positive coefficient on net purchases of bonds alone suggests opportunistic purchases of bonds when they are particularly cheap.

Table 4 reports the estimates of the interaction effect, d, in estimating equation (3) with each of the eight different insurer characteristics separately. The results show that, when the note becomes expensive relative to the bond, longer-horizon investors are net sellers of the note and net buyers of the bond, which suggests that they are taking advantage of the pricing differences, very much in line with the story of Amihud and Mendelson (1986). This also is consistent with the finding of Coval and Stafford (2007) in equity markets. When the note becomes expensive relative to the bond, the more leveraged insurers (with lower capital-to-asset and RBC ratios) tend to be net buyers of both the notes and the bonds, but buy the expensive notes more than the cheap bonds. In their choices of which assets to buy, the more leveraged insurers were therefore in effect exacerbating the mispricing. The two far-right columns of Table 4 also reports the estimated interaction effect, d, when estimating equation (3) with combinations of the different insurance characteristics jointly.

IV.3 Probit Regression

As a final approach to assessing the relationship between the trading behavior of insurers and their characteristics, we examine the propensity to purchase the relatively expensive note during various time periods. For the set of insurers buying either the note or the bond, we construct a 0/1 binary indicator that is 1 if a given insurer buys a note but not a bond in a given week, that is 0 if that insurer buys a bond but not a note, and missing otherwise. We exclude insurers that buy both the bond and the note (a very small set of insurers) and insurers that buy neither. We then run a pooled probit regression of this indicator on some of the insurer characteristics for five different subperiods: the pre-crisis period (January 1, 2006 – August 9, 2007), the crisis before Bear Stearns (August 10, 2007 – March 14, 2008), the crisis from Bear to Lehman (March 15, 2008 – September 14, 208), the immediate aftermath of the Lehman collapse (September 15, 2008 – December 12, 2008), and the subsequent period (December 13, 2008 – December 31, 2009). Table 5 shows the coefficient estimates for a number of specifications in all five subperiods. Note that the results in this table refer to whether an insurer bought a bond or a note, without regard to sales (unlike the previous section, which considered net purchases).

In all but one subperiod, none of the coefficients is statistically significant. The exception is the acute phase of the crisis from the demise of Lehman until December 2008. During this period, the better capitalized insurers were more likely to buy the expensive note than their less well capitalized counterparts. Thus it was the *least* distressed insurers that were buying the note, but outside of the crisis peak, there is no relative preference in securities for these investors.

V. Conclusions

In normal times, the pricing of different Treasury securities is internally consistent. Two different Treasury coupon securities with different coupon rates but the same maturity date will have almost identical yields. Indeed, one can form a portfolio combining either one of these coupon securities with a set of STRIPS such that the portfolio has exactly the same payoffs as the other security. The portfolio and the security should—and normally do—have almost exactly the same price; otherwise one could create riskless profits that should not exist in a well-functioning market.

However, starting with the onset of the financial crisis in August 2007, and then accelerating after the collapse of Lehman in the fall of 2008, these arbitrage relationships broke down dramatically. We find that the mispricing of Treasury securities documented by Hu, Pan, and Wang (2010) was systematic in nature and related to the liquidity features of securities that are correlated with their original issue maturity. Bonds that were originally issued as thirty-year bonds that had 6-9 years to maturity became much cheaper than bonds originally issued with a ten-year maturity, even though both had the same maturity date. The returns to a long/short strategy aiming to exploit the bond-note mispricing are not offset by net funding costs.

In the canonical theoretical model of persistent arbitrage opportunities, Shleifer and Vishny (1997) show that risk-aversion and bounded capital can explain why arbitrageurs are limited in their ability to prevent the emergence of pricing anomalies. In their model, "noise traders" have a liquidity-based motivation for trading that may cause prices to deviate from their fundamental value. Arbitrageurs trade against the noise traders to offset the deviations, but risk-aversion and limited capital can prevent the arbitrageurs from completely offsetting the divergence. The model explains why pricing discrepancies, and apparent arbitrage opportunities, can persist for some time. This paper aims to add empirical content to the Shleifer and Vishny (1997) model by characterizing the nature of the noise traders and arbitrageurs and offering clues as to their motivation.

Studying the unusual pricing of Treasury securities at times of market stress gives us useful insights into the behavior of fixed income markets at times when there are distressed asset sellers. We find that investors with longer horizons tend to exploit relative Treasury mispricings, which is intuitive as these mispricings represent a pure arbitrage from the perspective of a hold-to-maturity investor. We also find that more highly leveraged investors tend to exacerbate mispricings by buying the more expensive and more liquid security, transacting with an aim to obtain liquidity at any cost. The Treasury market environment allows for particularly clean analytical results and interpretation of these issues, but the lessons learned should have applicability to other fixed income securities and perhaps even to different asset classes.

It is useful for regulators and policymakers to understand when and why pricing anomalies occur. The transmission of monetary policy relies on arbitrage and tight pricing relationships between similar assets. For instance, in normal times, monetary policy works by influencing the overnight federal funds rate, but this then affects other interest rates, and hence the broader economy. And, in the recent period of quantitative easing, Fed purchases of Treasuries were intended to lower interest rates on high-quality private instruments. If arbitrage mechanisms break down, then so do these transmission channels of monetary policy. Moreover, asset price misalignments occur at times of financial instability, and so it is important to understand their origins and to identify the types of investors who are facing stresses.

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Figure 1 – The Arbitrage

This figure presents the time series of the difference between the yields to maturity on two Treasury securities: an original-issue 30 year bond and an original-issue 10 year note. Both securities mature on February 15, 2015. The bond was, originally issued in 1985 with a coupon of 11.25 percent; the note was originally issued in 2005 with a coupon of 4 percent.

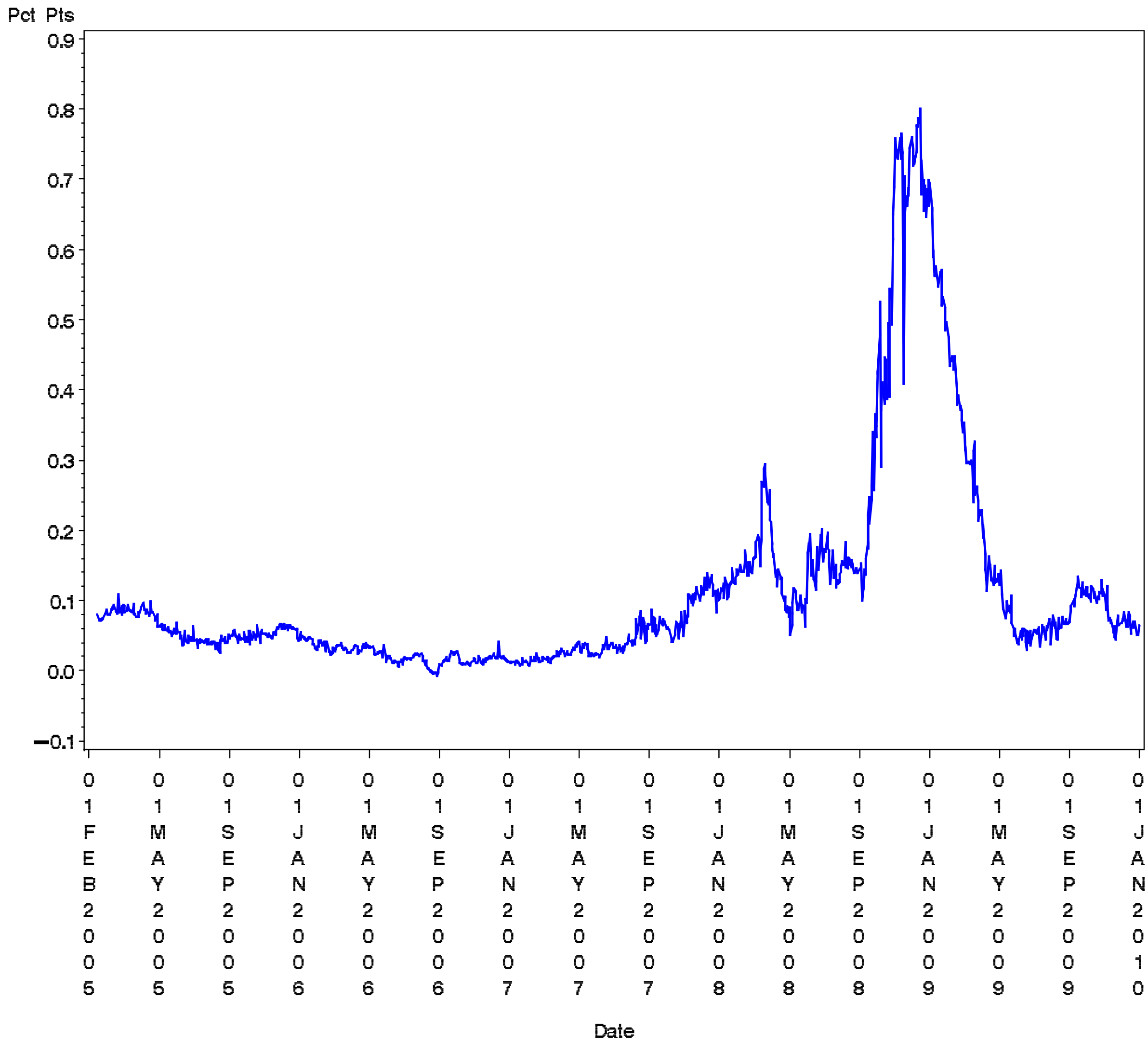

Figure 2 – Pricing Errors by Original-Issue Maturity

This figure presents the average pricing errors for three original-issue maturity buckets: thirty-year bonds, ten- year notes, and five-year notes. The pricing error is defined as the difference between the actual price of the security and the fitted price based on a smoothed yield curve. The vertical axis is measured in percentage points.

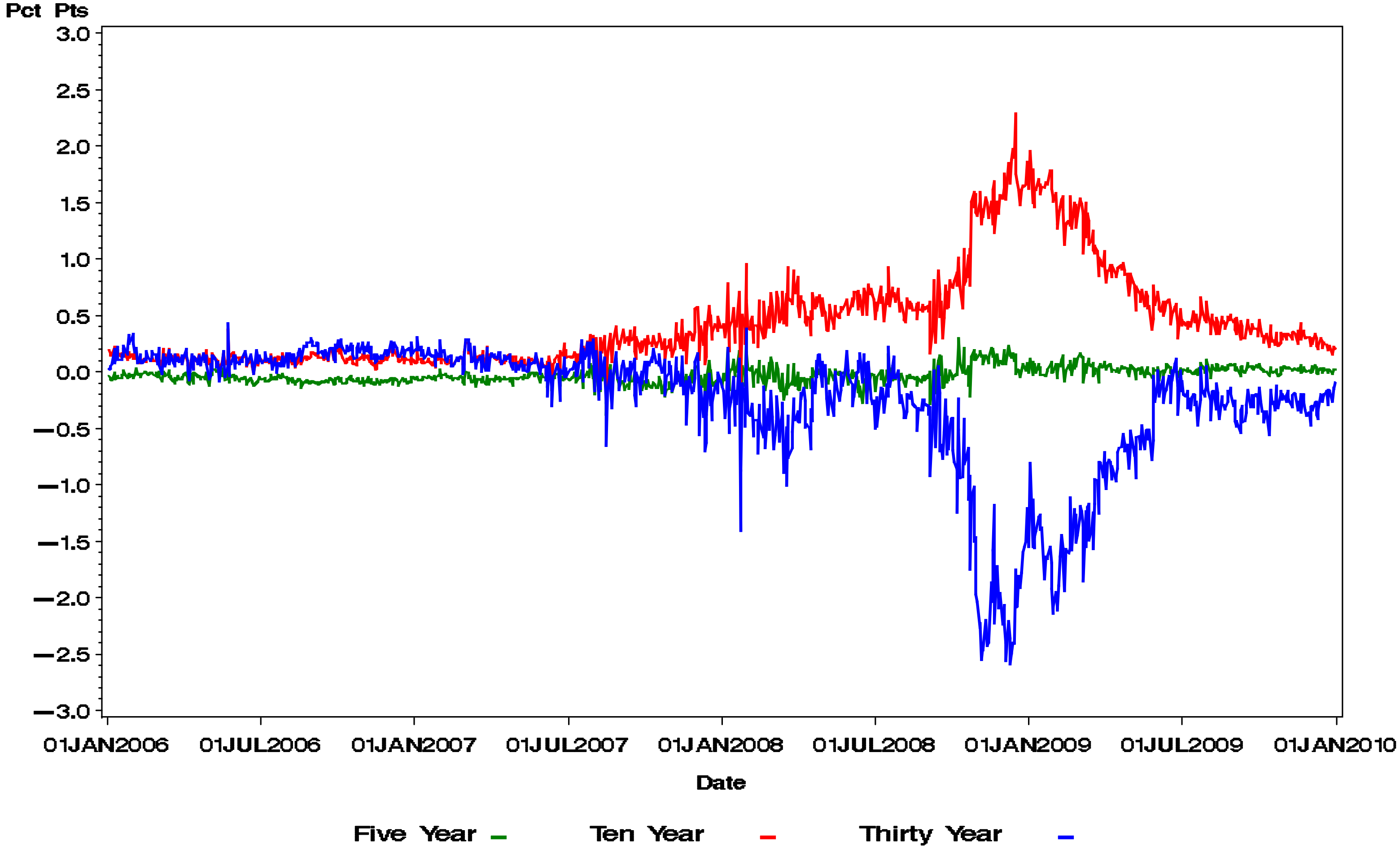

Figure 3 – Arbitrage Profits versus Funding Costs

This figure presents the monthly return on the convergence trade (ignoring the special-GC spread) and the level of the special-GC spread for the bond-note pair maturing on February 15, 2015.

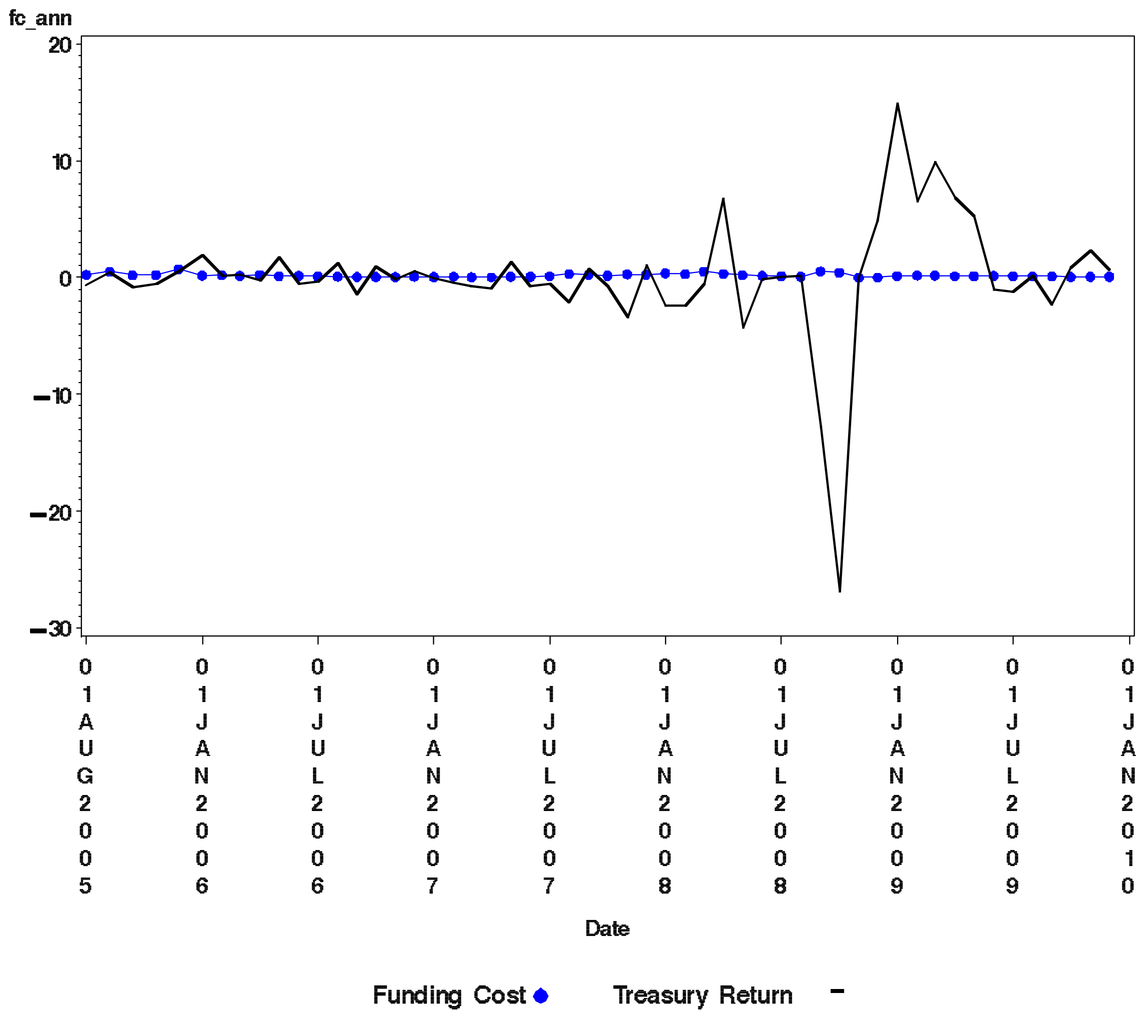

Figure 4 – Arbitrage Profits versus Funding Costs

This figure show the monthly frequency of Treasury specials transactions from a large inter-dealer broker on the left axis and the monthly volume of Treasury fails to deliver on the right axis (in $ billions).

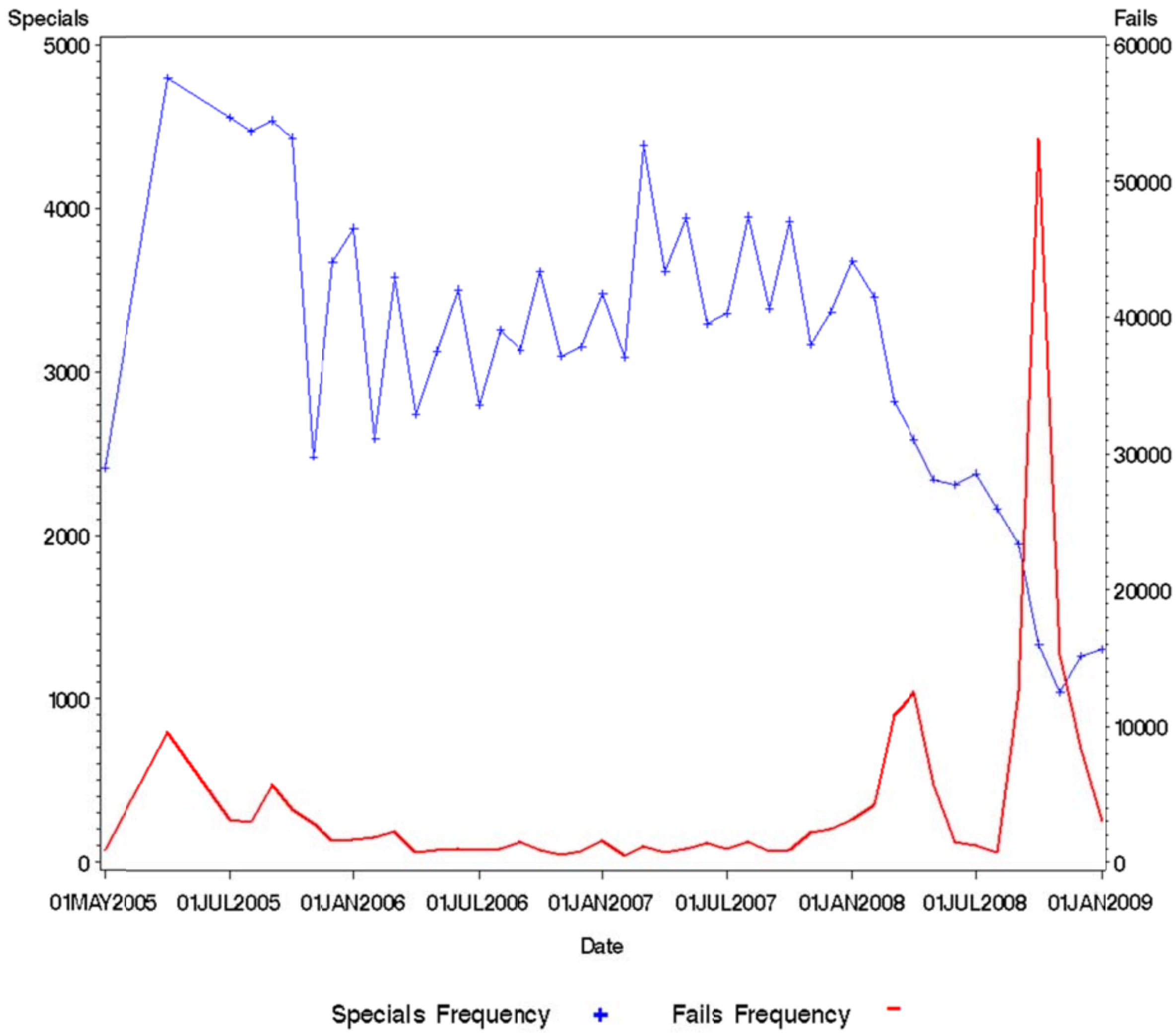

Table 1 – Bond/Note Pairs

Number of Pairs	9
Maturity Date Range	2/2015 - 5/2018
Bond Issue Date Range	2/1985- 5/1988
Note Issue Date Range	2/2005 - 5/2008
Average size of Notes (10Y)	$26 bn
Average size of Bonds (30Y)	$14 bn
Average Yield Spread (Bond – Note)	0.09%

Table 2 – Cross-Sectional Characteristics of Pricing Errors

This table presents a regression of pricing errors on several bond characteristics: ln(outstanding) is the log of the dollar amount of the bond outstanding, ln(bid-ask) is the log of the dollar difference in quoted bid and ask prices, and the other three variables are dummy variables indicating the original issue maturity of the bond. The pricing error is defined as the difference between the actual price of the security and the fitted price based on a smooth forward rate yield curve. The sample period is January 1, 2005 through December 31, 2010. The crisis period is from September 1, 2007 to June 30, 2009. Standard errors (in parentheses) account for clustering within bond cusip and arbitrary heteroskedasticity; ** (*) denotes estimates that are statistically significantly different from zero at the 1(5)-percent level.

	Dependent Variable: Pricing Error	
	Full Sample	Crisis Period
Intercept	-2.232**	-4.505**
	(0.747)	(1.792)
ln(outstanding)	0.136**	0.281**
	(0.044)	(0.107)
ln(bid-ask)	0.034	0.092**
	(0.022)	(0.036)
Original issue 30-year	-0.144	-0.378**
	(0.075)	(0.121)
Original issue 10-year	0.342**	0.671**
	(0.041)	(0.079)
Original issue 5-year	0.070**	0.147**
	(0.023)	(0.054)
R-Squared	0.231	0.407
Observations	149,228	46,192

Table 3 – Time Series Characteristics of Pricing Errors

This table presents a daily time regression of average portfolio pricing errors for nine bond-note pairs on several macro measures of liquidity: the average bid-ask spread on repo transactions (Repo B/A Spread), the repo rate for general collateral Treasuries (GC Repo Rate), and the spread between Libor and the overnight indexed swap rate (Libor-OIS Spread). For each bond-note pair, the pricing error is the price difference between the note and a bond plus a STRIP that gives the identical cash flows to the note. The sample period is January 1, 2005 through December 31, 2010. The crisis period is from September 1, 2007 to June 30, 2009. Newey-West Standard errors (with 30 lags) are in brackets; Bold denotes estimates that are statistically significantly different from zero at the 1-percent level.

	Dependent Variable: Portfolio Pricing Error				
Freq. of Specials	**-0.22**				**-0.19**
	(0.06)				(0.06)
Libor-OIS		**14.03**			**9.59**
		(4.83)			(4.48)
Fails			**1.24**		-0.32
			(0.38)		(0.29)
Repo B/A				**15.80**	3.24
				(7.67)	(2.33)
R-Squared	0.44	0.22	0.13	0.05	0.50
Observations	942	1141	1160	1160	928

Table 4 – Who Engages in the Arbitrage?
Linear Regression

This table presents a pooled regression of net purchases of bonds less notes on the pricing error interacted with various characteristics of the insurance companies. Heteroskedasticity-robust standard errors are included in parentheses. Bold and bold italics denote estimates that are statistically significantly different from zero at the 5 and 10 percent levels, respectively.

Dependent Variable is Net Purchases of Bonds minus Notes										
Buy and Hold	**2.274**								-5.620	
	(0.654)								(5.570)	
Horizon		**1.301**							0.418	
		(0.374)							(1.885)	
Churn			**-0.791**						**-0.690**	
			(0.206)						(0.335)	
Assets				***-0.086***					-0.090	
				(0.048)					(0.056)	
Annuity					***-13.117***				6.076	***-11.536***
					(7.169)				(5.459)	(6.564)
EBITDA						***-0.155***			0.020	***-0.151***
						(0.081)			(0.035)	(0.081)
Cap/Assets							***0.068***		-0.056	0.018
							(0.041)		(0.055)	(0.044)
RBC								**0.056**	0.040	0.002
								(0.018)	(0.052)	(0.051)

Dependent Variable is Net Purchases of Notes										
Buy and Hold	**-2.943**								***9.131***	
	(0.635)								(5.403)	
Horizon		**-1.660**							-1.651	
		(0.366)							(1.836)	
Churn			**0.847**						***0.623***	
			(0.206)						(0.334)	
Assets				**0.102**					**0.108**	
				(0.048)					(0.055)	
Annuity					**16.179**				-6.630	**14.003**
					(7.034)				(5.349)	(6.424)
EBITDA						**0.174**			-0.029	**0.172**
						(0.080)			(0.035)	(0.080)
Cap/Assets							**-0.090**		0.049	-0.034
							(0.041)		(0.055)	(0.043)
RBC								**-0.070**	-0.037	0.009
								(0.018)	(0.052)	(0.051)

Dependent Variable is Net Purchases of Bonds										
Buy and Hold	**-0.600**								**2.965**	
	(0.147)								(1.329)	
Horizon		**-0.317**							**-1.025**	
		(0.073)							(0.418)	
Churn			**0.051**						-0.030	
			(0.014)						(0.020)	
Assets				**0.006**					**0.006**	
				(0.002)					(0.003)	
Annuity					0.982				-0.455	0.548
					(0.949)				(1.075)	(0.983)
EBITDA						***0.011***			0.001	***0.011***
						(0.006)			(0.006)	(0.006)
Cap/Assets							**-0.015**		-0.011	**-0.014**
							(0.006)		(0.008)	(0.007)
RBC								**-0.011**	0.005	0.007
								(0.005)	(0.005)	(0.005)

Table 5 – Who Engages in the Arbitrage?
Probit Regression

We construct a 0/1 indicator that is 1 if a given insurer buys a note but not a bond in a given week, that is 0 if that insurer buys a bond but not a note, and missing otherwise. This table reports the coefficients from pooled probit regressions of this indicator on selected characteristics for different subperiods. Standard errors are shown in parentheses. Bolded coefficients are significant at the 5 percent level.

	January 1, 2006-August 9, 2007				
Annuity	0.099				0.175
	(0.280)				(0.297)
EBITDA		-0.023			-0.024
		(0.015)			(0.016)
Cap/Assets			-0.001		-0.001
			(0.003)		(0.004)
RBC				0.445	0.339
				(0.685)	(0.735)

	August 10, 2007-March 14, 2008				
Annuity	5.275				5.282
	(14772)				(14741)
EBITDA		0.040			0.038
		(0.078)			(0.078)
Cap/Assets			0.004		0.001
			(0.006)		(0.007)
RBC				5.156	4.781
				(6.836)	(7.307)

	March 15, 2008-September 14, 2008				
Annuity	5.288				4.711
	(20149)				(20148)
EBITDA		0.045			0.044
		(0.112)			(0.128)
Cap/Assets			-0.009		-0.016
			(0.007)		(0.011)
RBC				0.043	3.120
				(1.948)	(3.299)

	September 15, 2008-December 12, 2008				
Annuity	**-0.824**				-0.728
	(0.367)				(0.555)
EBITDA		-0.030			-0.014
		(0.020)			(0.021)
Cap/Assets			**0.021**		0.013
			(0.009)		(0.014)
RBC				**0.001**	**0.002**
				(0.000)	(0.001)

	December 13, 2008-December 31, 2009				
Annuity	-0.667				-0.514
	(0.445)				(0.483)
EBITDA		-0.070			-0.046
		(0.037)			(0.039)
Cap/Assets			0.004		0.004
			(0.005)		(0.006)
RBC				1.470	0.644
				(1.942)	(1.901)