

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

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PRELIMINARY AND INCOMPLETE

Abstract: We relate market stress to asset pricing by analyzing a large and systematic discrepancy among off-the-run Treasury securities: for months during the crisis, bond prices traded far below otherwise identical notes, over five percent below at the peak, and orders of magnitude below what we find concurrent special repo rates to explain. This low lending revenue from holding the note begs the question why its current holders would not trade it for cheaper yet identical cash flows. To answer this question we look at the relative liquidity of the securities and the cross section of investors. Our data on Treasury security trading show that notes are more liquid than bonds, and insurers' transactions reveal that their note demand grows with their need for liquidity.

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

Abstract: We relate market stress to asset pricing by analyzing a large and systematic discrepancy among off-the-run Treasury securities: for months during the crisis, bond prices traded far below otherwise identical notes, over five percent below at the peak, and orders of magnitude below what we find concurrent special repo rates to explain. This low lending revenue from holding the note begs the question why its current holders would not trade it for cheaper yet identical cash flows. To answer this question we look at the relative liquidity of the securities and the cross section of investors. Our data on Treasury security trading show that notes are more liquid than bonds, and insurers' transactions reveal that their note demand grows with their need for liquidity.

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. 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 aim to answer two main questions. First, why did the anomaly become as large as it did and last as long as it did? Second, how can we relate the decision to buy, hold or sell the cheap bond or the expensive note to the concurrent circumstances of the trader of that security?

The fraction of the Treasury market held by insurers is modest, around 3%.¹ However, compared to other Treasury traders, insurers report their trades and differing circumstances in considerable detail. Thus, they present a unique opportunity to identify the motives underlying the decision to take the expensive or cheap side of this discrepancy. 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.

¹ The Federal Reserve's Flow of Funds data, Table L.209, shows the combined holdings of Life, Property, and Casualty Insurers, as of 12/31/2008, to be \$171 Billion, compared with the \$6.1 Trillion of Treasury securities (other than savings bonds) then outstanding (see <http://www.federalreserve.gov/releases/z1/current/z1r-4.pdf>).

The 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 bonds have higher coupons, and the notes are more liquid.

That the notes are more liquid is apparent in both tighter spreads and, for our insurance-company sample, in more transactions. The higher liquidity may reflect the larger issue sizes, the newer vintage, or post-issuance events, such as stripping (e.g. Jordan, Jorgensen and Kuipers, 2000), that affected notes and bonds unequally. But whatever the cause, relative liquidity, rather than relative coupon, is the focus of our analysis 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 over the bond.

Besides the underlying demand supporting the note over the bond, we also analyze the barriers to arbitrage, pushing prices back into alignment. 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 repos that were transacted turn 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 transactions largely dried up.

The scarcity of repo in the depths of the crisis could represent a friction in the repo market that prevented the supply of securities for loan from meeting the demand to borrow. Until May 2009, it was the market convention for a party that failed to deliver a Treasury security on one day to instead deliver the same security on the *next* day, at the *same* price. The penalty for failure to deliver was thus effectively being obliged to make an interest free loan. As discussed by Duffie (1996), Fleming and Garbade (2005) and Jordan and Jordan (1997), specials rates were nearly always bounded below by zero. This is because the reason why a party would borrow a security would be to make a delivery---but lending money at a negative interest rate would be more costly than simply failing on the delivery obligation. If a party faced unusual ancillary costs for failure to deliver, such as the risk of damaging a relationship with a counterparty, then it might have been rational for such a party to lend money at a negative interest rate in the specials repo market in order to avoid failing. However, failure to deliver in the Treasury market is common and does not ordinarily cause a significant loss of goodwill (Duffie (1996)). Prior to May 2009, instances of negative specials rates were extremely rare (Jordan and Jordan (1997) and Fleming and Garbade (2005))². With the zero lower bound on specials rates, and in a low interest environment, holders of securities were reluctant to lend them out because there was little benefit (the GC-special spread) and the material cost of probably having to wait a long time to get the security back.. Also, the lack of activity in specials market could reflect a lack of demand for arbitrage trades, as traditional arbitrageurs rapidly delevered, consistent with the literature on the limits to arbitrage (e.g. Shleifer and Vishny, 1998, Gromb

² Recognizing this friction, in May 2009 a minimum penalty for failing of 3 percent at annualized rate was introduced, and so the effective lower bound on specials rates is now -3 percent, but this is after our sample period.

and Vayanos, 2002, Vayanos and Vila, 2009, and Fontaine and Garcia, 2009), where short horizons or capital constraints interfere with betting on long-term convergences such as this trade.

The uniform and low credit risk of Treasury securities presents an unusually clean opportunity to compare the prices of identical cash flows, and has thus fostered a large and growing literature. Crisis-era Treasury anomalies are analyzed from this perspective in Hu, Pan and Wang (2010). Systematic price differences arise in normal times as well; there is the on-the-run/off-the-run spread analyzed in Krishnamurthy (2002), and spreads between Treasury bills and soon-to-mature notes analyzed in Amihud and Mendelson (1991) and Kamara (1994). The notes, they find, were consistently cheaper than the bills. Amihud and Mendelson (1991) attribute the difference to the bills' higher liquidity, whereas Kamara (1994) argues for the differential tax treatment that existed at the time. Strebulaev (2003) compares the yields of coupon securities with different original-issue tenors but identical maturity dates, and finds the premium for bills over notes not to correlate with standard liquidity proxies, and thus concludes that liquidity differences do not drive the premium. In Fontaine and Garcia (2009), Treasury-market price differences are related to funding liquidity and then integrated into a term structure model. A Treasury-market anomaly contemporaneous with the bond-note arbitrage is the TIPS anomaly documented by Fleckstein, Longstaff, and Lustig (2010).

Our analysis of the origins of the price disparity finds a strong cross-sectional relation between Treasury securities' liquidity, as revealed in new data on actual bid-ask spreads, and pricing. This relation grows even stronger during the crisis, though it cannot fully account for the magnitude of the disparity. In the cross section of investors we find those that otherwise exhibit longer horizons trade into the cheap bond, whereas those in more financial stress, as

measured by risk-based capital ratios, prefer the note, thus bidding it up. This indicates a feedback from financial stress to pricing of potential relevance to prudential regulation.

The plan for the remainder of this paper is as follows. In section II, we describe the bond-note pricing anomaly and the convergence strategy that is the focus of this paper. Section III 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 IV compares the investors on the two sides of the arbitrage, and Section V concludes.

II. The Bond-Note Arbitrage

In this section, we construct two portfolios with identical cash flows and show that, in normal times, they 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

Figure 1 shows an example of the bond-note pricing anomaly. The figure shows the spread between the yields to maturity on two Treasury securities, both maturing on February 15, 2015, one paying an 11.5% coupon and issued as a 30-year bond, and the other paying 4% and issued as a 10-year note. The bond's yield is seen to be generally just a few basis points higher until late 2007, when it starts climbing to a local peak around Bear Stearns in March 2008, and then on to an overall peak of 80 basis points in early December 2008. It is worth noting that both securities were well off-the-run during the time when the yield spread widened most notably; the note was over 3 years off the run while the bond was over 23 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, all else equal, 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, and so the pricing anomaly is even more pronounced than the matched-maturity bond-note pair would suggest.

For a precise comparison that accounts for the coupon difference, we create a synthetic portfolio of the bond and a Treasury STRIP to exactly match the cash flows of the note. 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 $1 - C_n / C_b$ on the bond principal STRIP. The excess price of the note over this replicating portfolio constructed from the bond is in Figure 2, which shows the same pattern as Figure 1, reaching \$2.05 per \$100 principal amount around Bear Stearns, and then peaking at \$4.98 on December 16, 2008.

In this paper we consider nine pairs analogous to the example in Figure 2. Each pair exhibits qualitatively the same behavior, though magnitudes vary. 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 that any money received at origination is, in the classical sense, an arbitrage opportunity. The amount of money received is what we refer to as the “pricing error.”

II.3 Funding Costs

An arbitrageur trying to seize this opportunity would face the cost charged by the repo market to short the note. That is, for most Treasury securities the repo rate is the same ‘General Collateral’, or ‘GC’, rate, but as Duffie (1996), Krishnamurthy (2002) and others observe, specific Treasuries can grow expensive to short, i.e. become ‘special’, where this expense manifests as a reduced repo interest rate. Securities that are being shorted as part of a salient arbitrage opportunity, such as the notes we study, would presumably be prime candidates to go

special. Since the arbitrageur would receive this special rate while paying the GC rate to finance the long side, the concern would be that the shortfall of the special rate from the GC rate would significantly reduce the trade's net funding cost. 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: the trade does converge but the average profitability is close to zero due to the shorting cost. The conclusion is that there is no genuine arbitrage opportunity in the old bond/new bond trade, at least in that sample period.

In some markets, properly-situated traders can ameliorate their shorting costs by failing to deliver the shorted securities. The cost of a delivery fail, explicit penalties aside, is essentially equivalent to the cost of borrowing the security with a zero-interest-rate repo, because either way, the seller gets zero interest on the sale proceeds. In Evans et al. (2009), failing is seen to be central to the cost of equity-options market making, as we see that, among other things, a major options market maker never borrows the underlying at a negative rebate. That was in the late 1990s, when failure to deliver equities was penalized more lightly than it is now. Similarly, failure to deliver Treasury securities was penalized more lightly before May 2009 than after.³ The potential economic significance of this is heightened by the very low prevailing federal funds target rates - 1.5%, 1% and 0 to 0.25% on October 8, October 29 and December 16, respectively, of 2008 – because, since the GC rate tends to track fed funds, these low fed funds

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 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 fact that there is now an explicit penalty for fails should influence the market for exploiting Treasury arbitrage opportunities now and going forward. This may help explain why the bond/note anomaly did not resurface during the recent strains in the Treasury market associated with the debt ceiling and the S&P downgrade.

rates mean that a failure to deliver has a low implicit penalty. And if these low penalties are not enough to compensate a repo counterparty for the risk that the repo imparts, then there will be no repos, only fails.

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 3 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

The period between August 2007 and May 2009 represented a period of extraordinary market turmoil, even in 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 show that deviations from the smooth curve were not just large, but systematic, with original-issue 30-year bonds growing cheap relative to original-issue 10-year notes. These bond-note pairs allow us to precisely identify arbitrage opportunities.

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 4 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.

The price disparities in Figure 4 focus attention on the differences between the bonds, and the key difference explored in Krishnamurthy (2002) and elsewhere is liquidity. To gauge this difference, we compare the securities' bid-ask spreads. Figure 5 shows the bid-ask spread for the ten-year notes versus the thirty-year bonds, using bid-ask data obtained directly from the TradeWeb platform. This platform comprises about three quarters of off-the-run Treasury trading volume. The thirty-year bid-ask spreads are wider than those of ten-year original issue securities, even prior to the crisis. While bid-ask spreads for both notes and bonds widen during the crisis, the bid-ask spreads of thirty-year securities spike more than seven-fold.

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

$$e_{it} = \alpha + \beta' X_i + \varepsilon_{it} \tag{1}$$

where e_{it} denotes the fitting error for the i th security on day t , and X_i is a vector of bond-specific characteristics. We use two sets of independent variables. First, as four proxies for liquidity we include; (1) the daily average of the quoted bid-ask spread, (2) the log of the

monthly size of amount of the bond outstanding (this accounts for repurchases and reopenings), (3) the log of the monthly quantity of stripping activity per issue, and (4) the log of the daily average time-to-last trade. 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 two-year, three-year, and seven-year notes. The regression includes observations from 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 second quarter of 2008 through the second quarter of 2009. The time-to-last-trade variable is only available as of June 2008, and so it is included only in the crisis sub-sample regression. Standard errors are heteroskedasticity-robust and clustered by CUSIP to allow for correlation in the error term for different observations of the same security.

The results are shown in Table 2. The coefficient on the bid-ask spread is negative and significant, suggesting that a larger bid-ask spread is associated with a relatively cheaper security. 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 the bid-ask spread is much stronger during the crisis and the R-squared value of the regression rises to 37 percent, 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, most notably during the crisis. 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. The regression is of the form

$$PE_t = \alpha + \beta' X_t + \varepsilon_t \quad (2)$$

where PE_t denotes the average yield spread across nine bond-note pairs on day t , and X_t is a vector of explanatory variables that includes (depending on the specification) combinations of the frequency of specials repo market transactions, the LIBOR-OIS spread, the volume of Treasury fails, the difference between note and bond Treasury bid-ask spreads, and the repo bid-ask spread.⁶ 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 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.

⁶ 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.

A plot of the monthly frequency of Treasury specials transactions and the monthly dollar volume of Treasury fails is shown in Figure 6. 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 Treasury bid-ask 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.

Insurance companies are natural candidates to consider as long-only investors who could trade in direction of arbitrage. They are investors with relatively predictable cash flows and long-duration liabilities. Krishnamurthy and Vissing-Jorgensen (2012) show that insurers are the most elastic class of investors with respect to Treasury supply changes. Furthermore, there is interesting variation within life insurers related to crisis.

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:

$$NP_{i,t} = \alpha_i + \beta_i PE_t + \varepsilon_{i,t} \quad (3)$$

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 :

$$\alpha_i = a + b' X_i, \quad \beta_i = c + d' X_i \quad (4)$$

Substituting (4) into (3) gives:

$$NP_{i,t} = a + b' X_i + c PE_t + d' X_i PE_t + \varepsilon_{i,t} \quad (5)$$

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 (5) 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 (5) with combinations of the different insurance characteristics jointly.

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 bid-ask spreads as measured from new

TradeWeb data and other 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.

It is a feature of financial crises that arbitrage relations break down, and it is critical for regulators and policymakers to understand why. This is true for a number of reasons. First, the breakdown in arbitrage relationships may make the crises more severe because financial institutions have based strategies on these relationships. Secondly, understanding the origins of mispricing can help to identify the types of investors who are facing stresses. Thirdly, 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. For all of these purposes, looking at the benchmark Treasury market is a particularly clean and very precise way to investigate break downs in pricing relationships during periods of market turmoil, and the lessons learned should have applicability to other fixed income securities and perhaps even to different asset classes.

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Appendix 1: Data

The securities considered in this paper are nominal coupon and principal STRIP Treasury CUSIPS reported as outstanding in the Monthly Statement of Public Debt of the U.S. Department of Treasury from June 1998 through March 2010, as well as interest STRIP CUSIPS for this sample period obtained from Bloomberg. This captures all such securities issued prior to March 31, 2010 that mature after June 30, 1998. The monthly statements also are our source for the time-varying amounts stripped as well as static security characteristics (coupon, issue date, maturity date). The Treasury's monthly statements report quantities stripped as of the last day of the month, so we denote the month-end value as the stripped quantity from that date until the end of the following month. We do not include Treasury Inflation Protected Securities (TIPS), Treasury bills, or Treasury bonds issued prior to 1985 (Treasury bonds issued prior to 1985 were callable). This gives us 1254 Treasury securities, of which 52 are bonds, 460 are notes, and the rest are principal and interest STRIPS. Of the Treasury coupon securities, 30 percent have an original issue maturity of 2 years, 29 percent of 5 years, 13 percent of 10 years, and 9 percent of 30 years.

The U.S. Treasury officially recognized Treasury "stripping" as part of the Federal Reserve's book-entry system in 1985 for newly issued securities with 10 or more years to maturity. This allowed market participants to trade principal and interest components of Treasury securities as separate securities. Each principal STRIP is assigned a unique CUSIP. For instance, two unique principal STRIPS mature on February 15, 2015; one stripped from the the 10-year note maturing on February 15, 2015, and on stripped from the 30-year bond maturing on February 15, 2015. However, interest STRIPS are fungible with other interest STRIPS maturing on the same date. The final interest payment stripped from the 10-year note maturing on February 15, 2015 is fungible with the final interest payment stripped from the 30-year bond maturing on February 15, 2015. Each maturity date corresponding to an interest STRIP is assigned a single unique CUSIP. So, there is only one interest STRIP CUSIP assigned to the February 15, 2015 maturity date. In 1997, Treasury expanded its STRIPS program to include all original-issue maturities. We find that each of the securities in our sample, with a maturity date after 2000, has been stripped.

We have intradaily Treasury price data as of May 3, 2004, from TradeWeb, a large customer-to-dealer electronic trading platform. From this platform, we form daily bid-ask

spreads as the average across 4 intradaily composite bid and ask prices from the TradeWeb platform. These data are unique in that inter-dealer trading platforms do not provide bid-ask data for off-the-run Treasury securities as trading on-the-run securities is their main business concern. Prior to 2004, we use CRSP price data for coupon Treasury securities. We also obtain daily amounts outstanding from CRSP.

We have specials Treasury repo price data from all fixed income transactions for a large inter-dealer broker from April 2004 through February 2009, totaling 153,907 specials trades. The data from this broker identify the specific security loaned, the date on which the trade took place, the trade settlement date, the maturity date of the transaction, and the transacted rate. There are 135,923 transactions where a specific Treasury security was repoed. Of these, 90 percent show a Treasury note repoed, while 9 percent show a Treasury bond repoed, and less than 1 percent show a Treasury STRIP repoed. Of the repoed notes, 88 percent of the securities repoed were either 2-year, 5-year, or 10-year original issue (25 percent 2-year, 33 percent 5-year, and 30 percent 10-year). 76 percent of Treasury repos from this broker are overnight transactions with same-day settlement, and 99 percent are one-week or less in maturity. We treat transactions that occur on a Friday and maturing the following Monday to be overnight trades. The longest maturity Treasury transaction in this data sample is 418 days. We observe 1033 transactions that take place at a repo rate of 0, where cash is effectively borrowed for free in exchange for a specific Treasury security as collateral. We observe 5 transactions that take place at a negative rate; 4 out of the 5 occur in November 2008, and 1 occurs in April 2008. So, while there is no explicit economic incentive to pay to lend cash against some particular security, this does indeed occasionally (though rarely) occur.

We also have a specials Treasury repo price data sample from a large dealer, including rates for all this dealers specials transactions. This data sample spans January 2004 through May 2008. We use the inter-dealer broker sample for our analysis, but we fill in rates from the dealer sample for CUSIPs that the dealer trades but the broker does not for a given date. There may be some concern about sample selection in adding dealer repo rates to the broker repo rate sample, however they show many of the same securities traded on many days. The summary statistics of the difference in these rates show a mean very close to zero, 0.002, a median and mode of 0. There is a negative skewness to the difference in rates, -2.84, suggesting that the dealer pays

slightly more to borrow cash against a particular security than the average dealer that transacts via the inter-dealer broker.

Daily general collateral Treasury repo bid-ask spreads are computed as the difference between GC Treasury repo and GC Treasury reverse repo rates, obtained from Bloomberg.

Weekly fails data from the Federal Reserve show failures to deliver and failures to receive by primary dealers across all Treasury securities. These reflect either outright or temporary Treasury transactions that have not settled on the scheduled date. While primary dealers reflect the vast majority of Treasury trading volume, they do not represent the entire universe, and therefore the sum of primary dealers' failures to receive does not necessarily equal the sum of their failures to deliver. We use the average of the failures to deliver and failures to receive from the Federal Reserve primary dealer system.

Finally, insurer holdings and transactions data come from eMAXX. Insurance funds are required to report daily transaction dates, quantities, and prices as well as quarterly holdings on Schedule D filings, which are then collected by eMAXX. Transactions that have identical date, CUSIP, price, and quantity are summed and considered to be a single transaction. When it is not clear with whom the fund has transacted, eMAXX denotes the trade as split evenly across investment advisors that typically work with the fund. For cumulative purchases and sales, we consider the starting value to be the initial holding value from our quarterly holdings data. Cross-sectional insurance fund characteristics are gathered from SNL, and are matched with the eMAXX data by insurance fund name.

Our holdings and transactions data samples are from the end of the second quarter of 1998 through the end of the 1st quarter of 2010. The holdings data show 3105 unique firm IDs and 2,103,254 observations for firm i , cusip j , and quarter t . The observations fall by 9.8 percent when bills, TIPS, and callable Treasuries are eliminated. The transactions data show 1360 unique firm IDs and 218,741 observations for firm i , cusip j , and date t . The transactions are cut by 7.1 percent when bills, TIPS, and callable Treasury trades are eliminated. Fewer transactions than holdings observations are seen because cusip/insurer/quarter combinations often do not show any change in holdings level (no buys or sells have occurred, but the holdings level is still reported).

If the insurer holdings data reflect a positive value for insurer i , cusip j at the start of the sample period, then cumulative purchases and cumulative sales of cusip j by insurer i reflect the purchases or sales added to the initial holding level of cusip j for insurer i at the start of the sample period.

Figure 1 – The Arbitrage in Yield Terms

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.

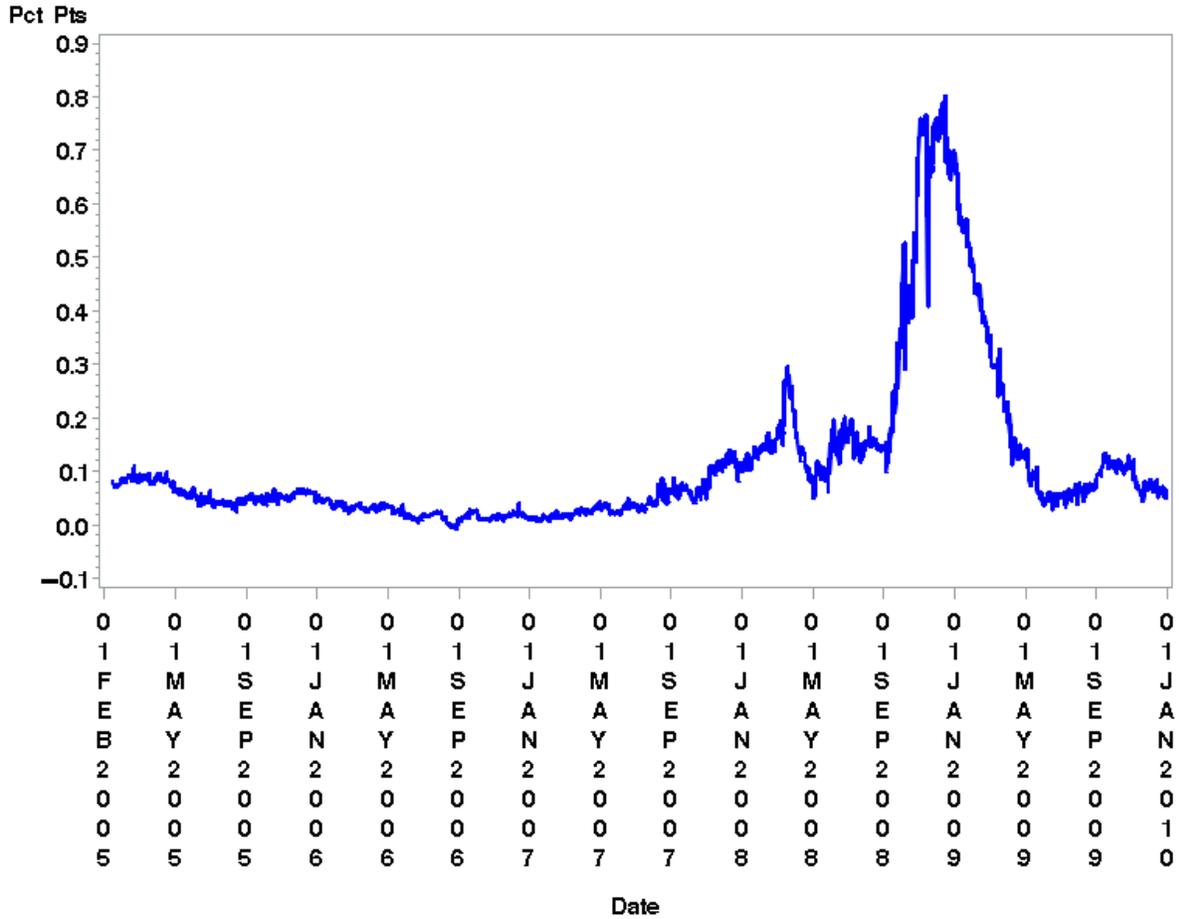


Figure 2 – The Arbitrage in Price Terms

This figure presents the time series of the difference between the prices on two Treasury security portfolios: an original-issue 30 year bond coupled with a STRIP versus an original-issue 10 year note. The bond, STRIP, and note all 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.

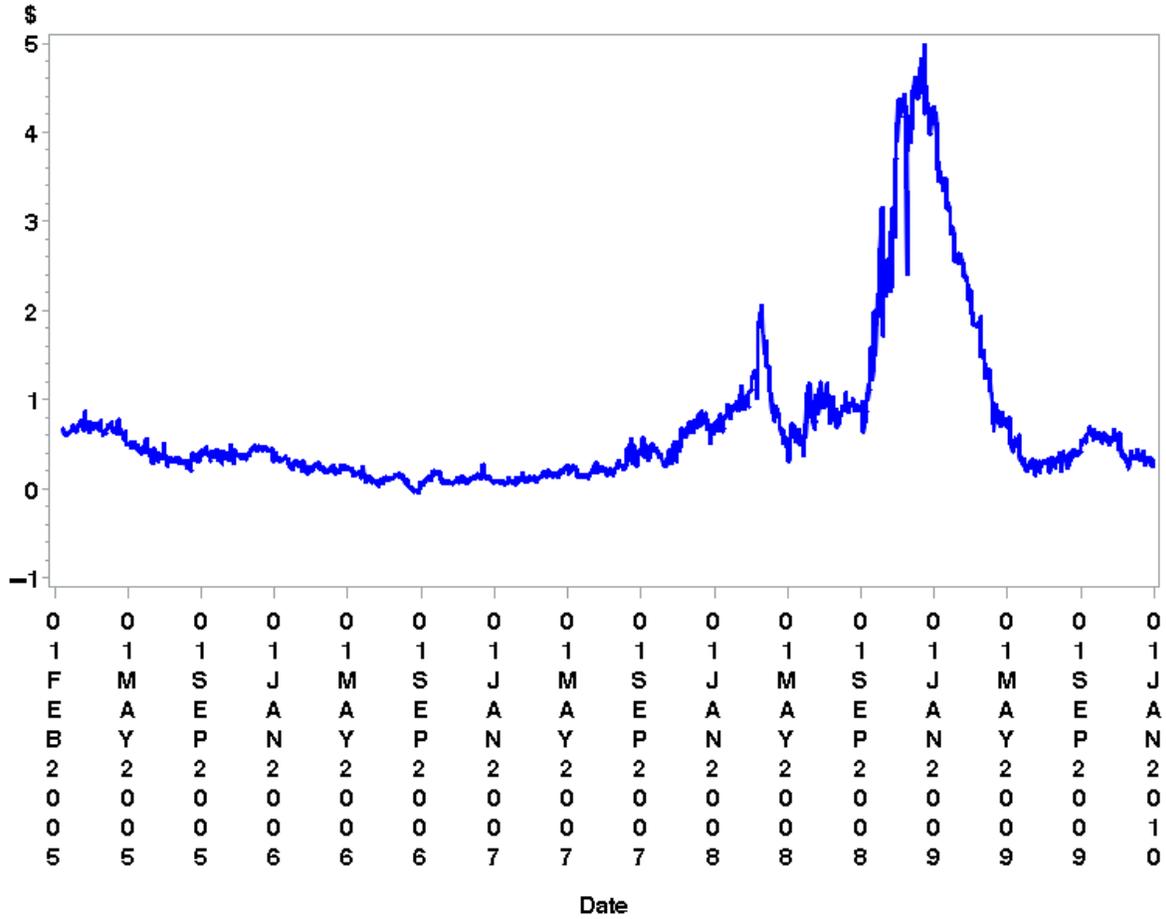


Figure 3 – Arbitrage Profits versus Funding Costs

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.

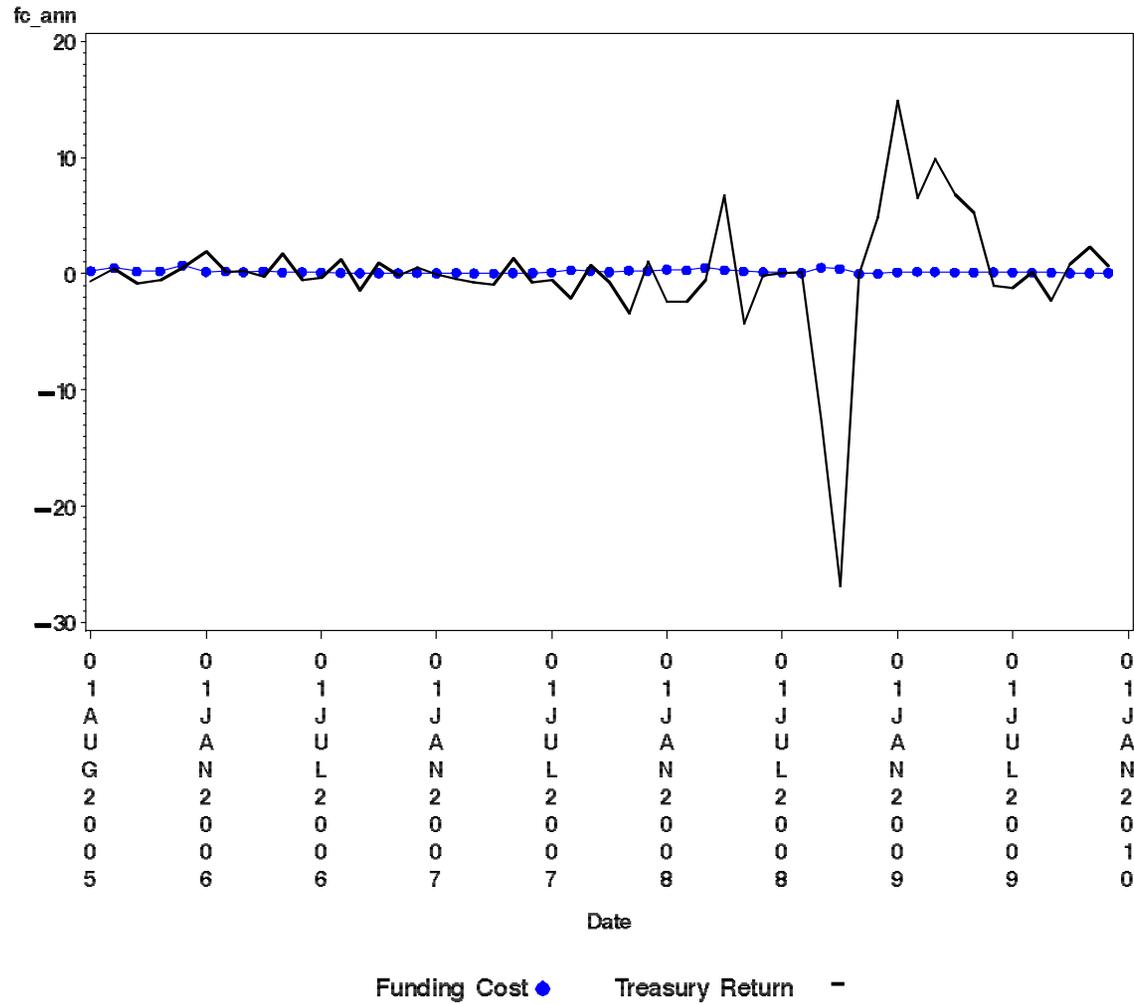


Figure 4 – Pricing Errors by Original-Issue Maturity

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.

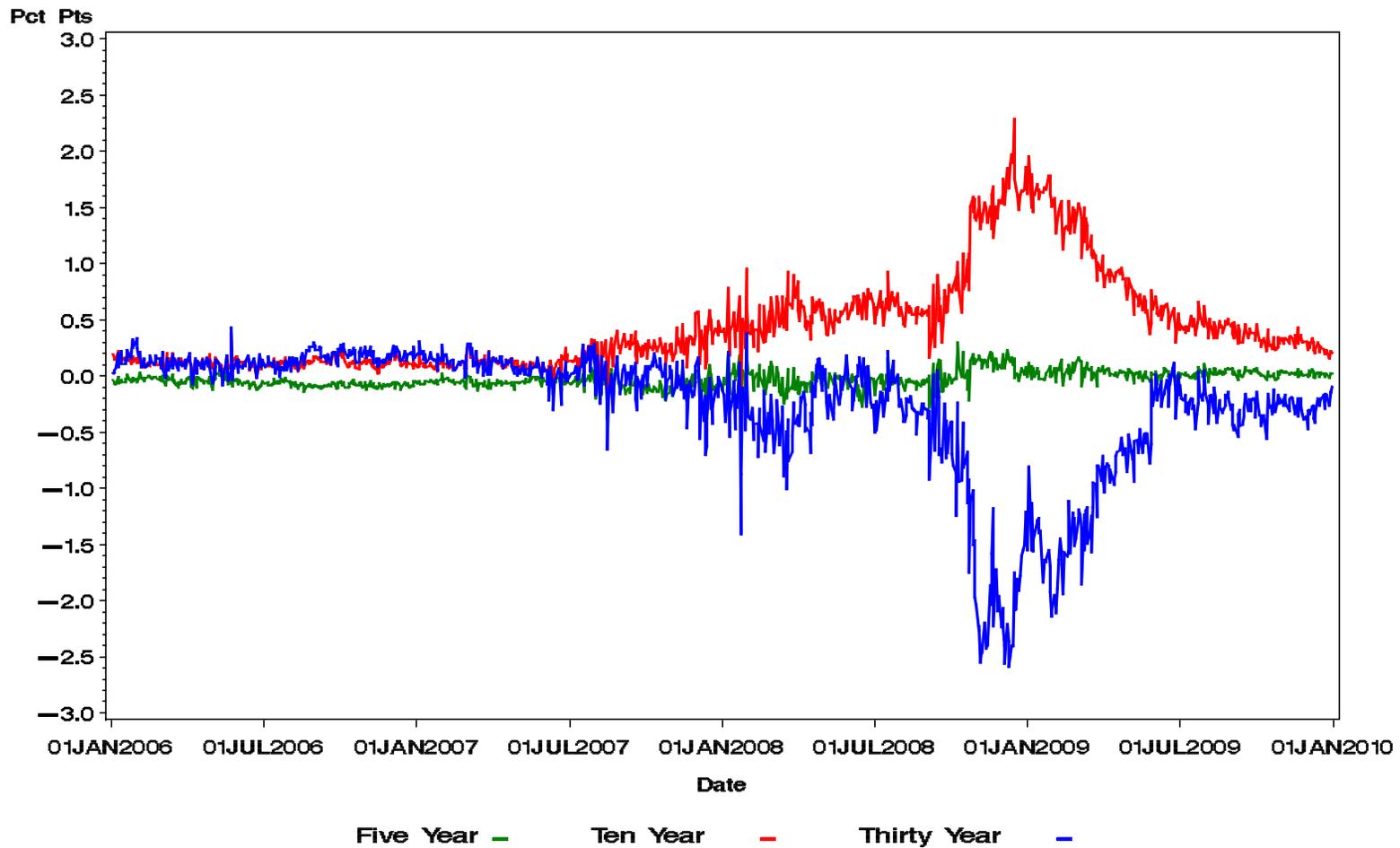


Figure 5 – Ten- and Thirty-Year Bid-Ask Spreads

This figure presents the daily bid-ask spread (in price terms), averaged across all off-the-run ten- and thirty-year original-issue maturity securities outstanding, from the TradeWeb platform. The vertical axis is measured in percentage points.

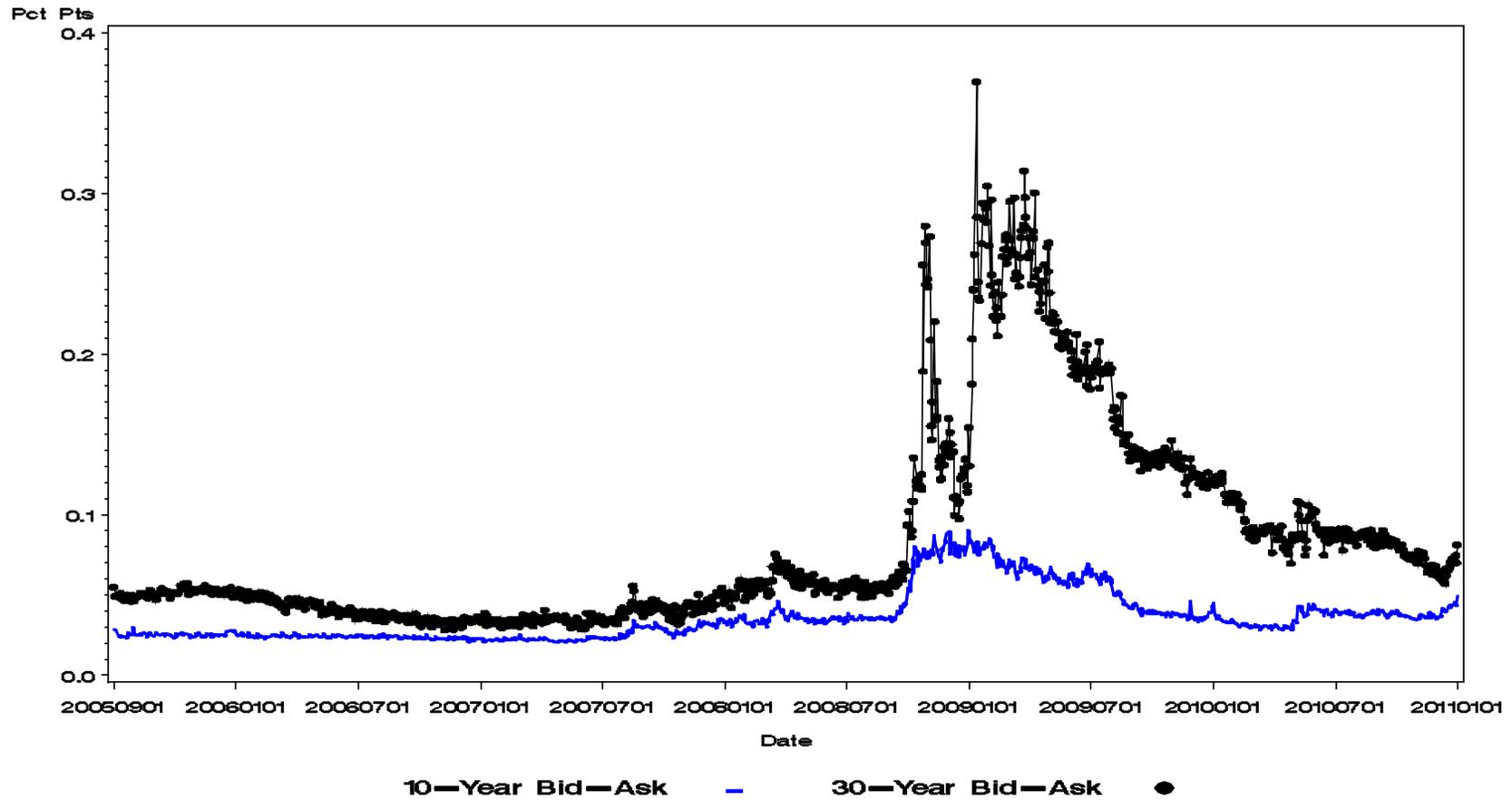


Figure 6 – Arbitrage Profits versus Funding Costs

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).

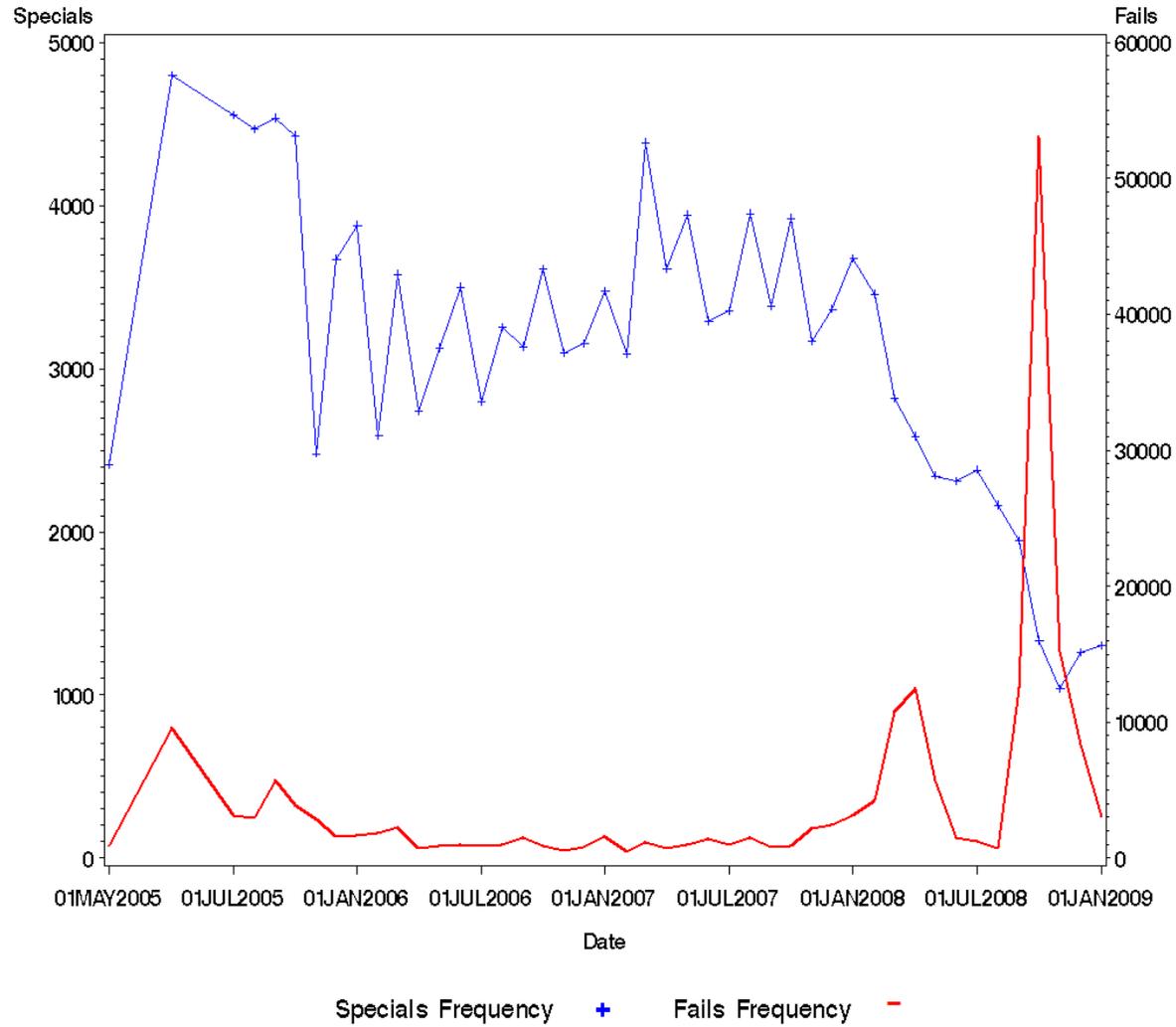


Table 1 – Bond/Note Pairs

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 – Liquidity Characteristics of Fitting Errors

This table presents a pooled regression of fitting errors on several bond characteristics: $\ln(\text{outstanding})$ is the log of the dollar amount of the bond outstanding, $\ln(\text{bid-ask})$ is the dollar difference in quoted bid and ask prices from TradeWeb, $\ln(\text{stripping})$ is the log of the monthly quantity stripped for each security, $\ln(\text{time-to-trade})$ is the log of the daily average time between trades, and the other three variables are dummy variables indicating the original issue maturity of the bond. The fitting error is defined as the difference between the actual price of the security and the fitted price based on a smoothed yield curve. The sample period is January 1, 2005 through December 31, 2010. The crisis period is from June 30, 2008 to June 30, 2009. Standard errors (in parentheses) account for clustering within bond cusip and arbitrary heteroskedasticity; Bold denotes estimates that are statistically significantly different from zero at the 1-percent level.

	Dependent Variable: Fitting Error								
	Full Sample			Crisis Period					
Intercept	-2.56 (0.95)	0.21 (0.09)	0.02 (0.01)	-0.09 (0.92)	-8.38 (3.19)	-0.06 (0.04)	-0.01 (0.02)	0.08 (0.05)	-8.41 (3.16)
$\ln(\text{outstanding})$	0.15 (0.06)			0.02 (0.05)	0.48 (0.19)				-0.92 (0.27)
$\ln(\text{stripping})$		-0.02 (0.01)		-0.02 (0.01)		0.00 (0.01)			0.49 (0.18)
bid-ask spread			-1.49 (0.49)	-1.83 (0.45)			-0.98 (0.30)		0.01 (0.01)
$\ln(\text{time-to-last-trade})$								-0.04 (0.02)	-0.02 (0.01)
Original issue 5-year	0.10 (0.04)	-0.01 (0.02)	0.02 (0.01)	0.02 (0.04)	0.33 (0.11)	0.06 (0.04)	0.08 (0.03)	0.08 (0.03)	0.34 (0.11)
Original issue 10-year	0.45 (0.06)	0.51 (0.06)	0.44 (0.06)	0.54 (0.06)	1.12 (0.15)	1.07 (0.14)	1.09 (0.15)	1.04 (0.14)	1.15 (0.14)
Original issue 30-year	-0.06 (0.09)	-0.14 (0.05)	-0.12 (0.05)	0.05 (0.09)	-0.37 (0.26)	-0.96 (0.11)	-0.72 (0.10)	-0.85 (0.10)	-0.24 (0.26)
R-Squared	0.1181	0.1194	0.1193	0.1318	0.4638	0.4426	0.4455	0.4473	0.4720
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 frequency of specials, the average bid-ask spread on GC repo transactions (Repo B/A Spread), the log of the incidence of fails, and the spread between Libor and the overnight indexed swap rate (Libor-OIS Spread), and the bid-ask spread on bonds minus the bid-ask spread on notes. 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						
In(Freq. of Specials)	-11.99					-6.75
	(3.04)					(2.62)
Libor-OIS		14.03				4.61
		(4.83)				(3.85)
In(Fails)			4.02			1.73
			(1.22)			(0.98)
Repo B/A				15.80		3.70
				(7.67)		(2.73)
Treasury B/A					81.81	82.18
					(0.15)	(0.15)
R-Squared	0.32	0.22	0.15	0.05	0.32	0.60
Observations	942	1141	1160	1160	1160	927

**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.

<i>Dependent Variable is Net Purchases of Bonds minus Notes</i>					
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	0.018
				(0.041)	(0.044)
RBC				0.056	0.040
				(0.018)	(0.052)
				(0.051)	
<i>Dependent Variable is Net Purchases of Notes</i>					
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
				(0.041)	(0.043)
RBC				-0.070	-0.037
				(0.018)	(0.052)
				(0.051)	
<i>Dependent Variable is Net Purchases of Bonds</i>					
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
				(0.006)	(0.007)
RBC				-0.011	0.005
				(0.005)	(0.005)
				(0.005)	