Liquidity and Asset Pricing: Evidence from the U.S. Treasury Securities Market*

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Comments welcome

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Abstract

This paper tests the illiquidity premium hypothesis using U.S. Treasury securities intraday interdealer data. In contrast to the existing literature where notes are matched with *bills* in terms of maturity date, we compare notes with other *notes* maturing on the same day. One reason for comparing notes with notes rather than notes with bills is that differences in tax treatment across bills and notes could confront an experiment to measure the illiquidity effect. We find that notes are quoted at essentially identical prices despite substantial differences in their liquidity. This rejection of the hypothesis is in sharp contrast to the result of previous studies (Amihud and Mendelson, 1991). Therefore we reconsider the evidence based on matched bills and notes. We identify cross-sectional variation in bill-note pricing differences that cannot be supported by the illiquidity premium hypothesis. We also show that the pricing difference is smaller for matches with on-the-run bills, although the difference in liquidity between these bills and notes is significantly larger.

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1 Introduction

The role of market imperfections, particularly liquidity factors, for securities pricing has attracted considerable attention from both practitioners and academics. One of the main theories of the impact of liquidity on asset prices is the illiquidity premium hypothesis proposed by Amihud and Mendelson (1986). It states that the market-observed expected return should be an increasing and concave function of liquidity (typically measured by the bid-ask spread). The intuition is that the present value of all future trading costs should be reflected in the security price; since securities with wider bid-ask spreads involve higher trading costs, investors should demand higher rates of return for holding them. Therefore, a pair of otherwise identical securities differing only in liquidity should differ in price.

Empirical tests of the hypothesis are difficult since in most markets securities usually differ in many dimensions, including the price of risk. Consequently, the most compelling evidence in support of the hypothesis probably comes from the US Treasury securities market, where identical pairs of securities are easier to approximate. In particular, Amihud and Mendelson (1991) match Treasury notes with Treasury bills[1] with (approximately) the same maturity date. With less than six months to maturity, notes become zero coupon securities and provide the same cash flows to investors as bills. Amihud and Mendelson show that compared to bills, notes (known to be less liquid than bills) are substantially cheaper, which they conclude is evidence in favor of the illiquidity premium hypothesis.

This paper tests empirically the illiquidity premium hypothesis using U.S. Treasury securities intraday interdealer data over the sample period 1995-97. Our initial step is to improve the matching by pairing different U.S. Treasury notes, i.e. with different initial maturity, but maturing on the same day. We strongly reject the illiquidity premium hypothesis: although the matched notes differ substantially in their liquidity (as measured by bid-ask spread etc.), there is no economically significant difference in their pricing. In particular, we find that the mean difference between ask yield on a less liquid note and ask yield on a more liquid note (pooling all observations) is slightly negative at -1.0 basis points (b.p.)[2] and between bid yields is 0.6 b.p. These differences are substantially

[1]Treasury notes are securities with initial maturity exceeding one year, while Treasury bills are securities with initial maturity of one year or less.

[2]A basis point is $\frac{1}{100}$th of 1%.

smaller than corresponding bid-ask spreads of the matched notes, demonstrating the economic insignificance of the difference. We also estimate an intuitive measure of arbitrage opportunity – the difference between the ask yield on a less expensive asset and the bid yield on a more expensive one. In the absence of imperfections this measure would be nonpositive. The measure of arbitrage is negative at -4.0 b.p.

This result is in sharp contrast to the conclusions of earlier studies based on US Treasury securities market (Amihud and Mendelson, 1991; Kamara, 1994) that match *bills* and *notes*.[3] Using daily quotes from a primary dealer over a 37-day interval in 1987, Amihud and Mendelson find that the average difference between ask prices of matched bills and notes is 43 b.p. in annualized yield. Using monthly observations over the period 1977-84, Kamara also finds significant difference between matched bills and notes. Comparing bills and notes with 14 weeks remaining to maturity, he finds the mean yield difference to be 34 b.p.

Therefore, we reconsider the bill-note comparison using our data set. We begin by replicating previous studies by matching bills and notes. We also find a significant (though somewhat smaller) difference between the prices of matched bills and notes. We find the difference between non-indicative ask quotes to be 10.2 b.p. in annualized yield for the maturity range from 4 to 26 weeks. Furthermore, the mean estimation of our measure of arbitrage is 7.7 b.p. or 2.1 cents per $100. This amounts to $2100 to-be-profit per $10 million trade, which is typical in these markets. The average bid-ask spread is around $600 for the same trade, indicating the economic significance of the price difference.

There are, however, several reasons why the matching of bills and notes may be less than perfect. First, other market imperfections such as taxes, specialness of some securities and new bills issues may play a significant role for pricing. Second, the market for bills is very heterogeneous: liquidity differs dramatically between on-the-run and off-the-run bills, making it difficult to compare bills and notes. Third, the markets for bills and notes have different institutional features that can affect their bid-ask spreads.

To investigate whether these (or other) reasons indeed affect the bill-note comparison, we proceed by running two new tests. In both tests we disentangle our sample into

[3] Garbade (1984) was the first to suggest a matching of similar Treasury bills and Treasury notes. We are not aware of similar studies in foreign markets.

subsamples of bills-note matches, and test the hypothesis' cross-sectional predictions, i.e. implications for the relative sizes of pricing differences among subsamples. In both cases, our findings are inconsistent with the illiquidity premium hypothesis, suggesting that other factors affect the pricing difference between bills and notes. We conclude therefore that while liquidity factors may play a role in explaining price differentials, they do not explain cross-sectional variation in pricing difference between matched bills and notes.

In our first test, we construct subsamples of bill-note matches in which notes have the same initial maturity (ranged from two to ten years). We confirm the significant pricing difference for all types of notes. We also find a significant cross-sectional variation in the pricing difference between bills and notes. The illiquidity premium hypothesis predicts that these pricing differences are increasing with notes bid-ask spreads. However, we find the actual ranking to be inconsistent with the ranking of the notes bid-ask spreads. For instance, while two-year notes are the most liquid among notes in this maturity range, the price differences between matched bills and two-year notes exceed substantially those for three and ten-year notes.

In the second test, we distinguish between matches where a bill is on-the-run On-the-run bills are the most recently issued in its maturity class, while off-the-run are all-other bills. We find that liquidity is significantly improved when bills are on-the-run, falling to the level of notes immediately after they become off-the-run. The theory predicts difference in prices be not smaller for matches with on-the-run bills. However, the price difference is found to decrease when bills become on-the-run and then increase when bills become off-the-run. Again, this is inconsistent with the illiquidity premium hypothesis.[4] Our findings suggest that the link between liquidity and asset pricing is not captured by the illiquidity premium hypothesis.

The illiquidity premium hypothesis has been tested on U.S. and other stock markets data. The evidence is mixed. Amihud and Mendelson (1986) find evidence supporting the illiquidity premium hypothesis using U.S. stock market data. However, Eleswarapu and Reinganum (1993) question that result attributing the finding to seasonal patterns.

[4]To check the robustness of the findings, we also use for all tests other proxies for liquidity such as turnover, number of quotes and trades, and trading volume (e.g., see Lee, 1993). Our qualitative results are unchanged.

Unlike these authors, who used the standard capital asset pricing model to adjust returns for risks, Brennan and Subrahmanyam (1996) find significant relation between required rates of return and illiquidity, using a three-factor Fama and French (1993) model. The main issue when using stock returns for testing liquidity theories is that besides other imperfections, the market price of risk should be accounted for. Measurement error in estimating the latter may outweigh all liquidity effects. Unlike stocks, government bonds have known nominal cash flows and fixed maturities. All risks embedded in these securities, conditional on their cash flow identity, like term structure and adverse selection risk, should be the same. This is the rationale of using U.S. Treasury securities market as a field for testing liquidity theories. The idea of matching essentially identical securities has been used in a number of studies.[5]

The paper proceeds as follows. Section 2 summarizes some features of the secondary market for U. S. Treasury securities. Section 3 describes the data and the procedure for calculating the prices of securities and matching them. Section 4 gives the main empirical results and provides economic explanations. Section 5 concludes. Appendix A provides a detailed description of the data and the procedure employed to clean it.

2 The Secondary Market for U.S. Treasury Securities

In this section we describe some of the main features of the secondary market for U.S. Treasury securities that are important for our study. A number of other markets for Treasury securities exist that may affect prices of securities in the secondary market. They include futures, when-issued, and repo markets as well as auctions for newly issued

[5]Froot and Dabora (1999) compare "Siamese twin" companies whose shares are traded around the world. Bodurtha, Kim and Lee (1995), Chen, Kan and Miller (1993), Lee, Shleifer and Thaler (1990, 1991), among others, document closed-end funds anomaly. Daves and Ehrhardt (1993), Grinblatt and Longstaff (2000), and Jordan, Jorgensen and Kuipers (2000) compare U.S. Treasury principal and coupon STRIPs, and also compare notes and bonds with the same securities but reconstituted using STRIPs, finding small but pervasive pricing differences. Dimson and Hanke (2000) study equity index-linked bonds providing the same payoff as an investment in an equity index. Although these papers include liquidity factors as a potential explanation of found mispricings, none of them study the illiquidity premium hypothesis directly.

securities. To pair identical securities we use only the secondary market.[6]

While this market is one of the largest in the world in terms of trading volume, the number of transactions is actually quite small. Indeed, the interdealer over-the-counter market is mainly the wholesale market, with minimum trade and quote sizes of $1 million, the average trading size for all securities being roughly $12 million.

This market is organized predominantly as an over-the-counter market,[7] comprising of dealers, brokers, institutional and private investors, including foreign investors, all of which are actively making the market. Although some 1700 brokers and dealers operate in this market,[8] a few primary dealers (i.e., the firms with which the Federal Reserve conducts its open market operations) constitute the largest segment of the market in quoting, trading activity and volume. Currently there are 35 primary dealers, each of whom stands ready to buy a security at a stated bid quote in a size of a stated depth and sell a security at a stated ask quote in a size of a stated depth.

A dealer can make a quote or a trade with another dealer either via a direct connection with another dealer (e.g. over the telephone), or via the screen of an interdealer broker. In the latter case the identity of the dealer is not revealed. Interdealer brokers provide matching of demand and supply and charges a small commission per trade. During the sample period 1995-97, there were six interdealer brokers. They hold the largest portion of the market. Quotes can be non-indicative or indicative. Non-indicative (or firm) bid quote can be considered as an obligation of a dealer to buy a security at a quoted price in the size of or below stated quoted depth. The market convention is that notes and bonds are quoted in (clean) prices, while bills are quoted in discount rates. Most of trades

[6]Stigum (1990) and Sundaresan (1997) discuss the organization of this and other fixed income markets in greater detail. The when-issued market for those securities which are already announced to be auctioned but not issued yet constitutes an important area of U.S. Treasury securities market. See Bikhchandani and Huang (1993) and Nyborg and Sundaresan (1996) for details. We do not consider the when-issued market in our study since liquidity in this market may reveal significantly different patterns of behaviour than in a secondary market due to the possibility of strategic bidding of dealers at the time of auction. The repo market, where security plays a role of collateral in borrowing, may play an important role if a particular security is scarce.

[7]U.S. Treasury securities are listed on NYSE. However, trading volume is negligible in comparison with the over-the-counter market.

[8]see *Joint Report on the Government Securities Market* (1992).

occur between dealers themselves or between dealers and their customers, though trades between dealers constitute the largest segment of the market. Transactions are usually settled in one business day.

All outstanding issues of U.S. Treasury securities have different legal natures.[9] This means that these securities are quoted and traded separately, and cannot be returned if borrowed in exchange for another security even if they provide essentially the same cash flows.

Issuance cycles differ across securities. Treasury bills are issued weekly. Two and five-year notes are issued on a monthly basis, while three, seven and ten-year notes on a quarterly.[10]

3 Data

3.1 The GovPX System

The data set used in this paper comes from GovPX, an organization set up by all the primary dealers and a majority of interdealer brokers serving the U.S. Treasury market.[11] This data set consists of all trades and quotations registered through participating interdealer brokers.[12] It is the first intraday data set covering a long period of U.S. Treasury secondary market.

The GovPX system collects quotations from the interdealer screens. When a dealer places a new (firm or indicative) quote on one of these interdealer systems and this quote

[9] In a few rare cases the Treasury may issue note with the same CUSIP (identification number, that is a legal determinant of a security), mainly if for existing note with the same maturity as auctioned one coupon rate is the same.

[10] All this information is relevant for the 1995-1997 period. The U.S. Treasury stopped issuing seven-year notes, therefore there are only a few of them. Also, the U.S. Treasury used to issue five-year notes with exact maturity being equal to five years and $2\frac{1}{2}$ months. There are a few such notes in our data set, that we exclude.

[11] GovPX was set up in 1990 to provide greater market transparency and greater dissemination of U.S. Treasury prices.

[12] The following interdealer brokers comprised GovPX during the sample period 1995-97: Garban Ltd., Hilliard Farber & Co. Inc., Liberty Brokerage Inc., RMJ Securities Corp., and Tullett and Tokyo Securities Inc. The sixth broker, Cantor Fitzgerald Inc., is not a part of this system.

improves on the existing one, it is instantly registered in the GovPX system as a separate observation.[13] The time of quotation, the characteristics of the security quoted, the ask and/or bid price, and the ask and/or bid suggested depth are also recorded. Actual trades are recorded as separate observations. In addition to stated inputs, the trade price, the side originating the deal (hit or take) and the size of the trade are also recorded.

Since different interdealer brokers use different tick conventions, GovPX reports bill prices, quoted at discount rate, in $\frac{1}{10}$th of a basis point and those of coupon-bearing securities, quoted at (clean) prices per \$100 of principal payment, in $\frac{1}{8}$th of $\frac{1}{32}$nd of one dollar (i.e., the tick size is approximately 0.391 cents per \$100 principal payment).

The GovPX data set (or part of it) has been used in several studies, e.g., by Nyborg and Sundaresan (1996), Elton and Green (1998), Green (1999), Balduzzi, Elton, and Green (1997), and Fleming and Remolona (1998, 1999). All these papers use GovPX data set for 1991-95 years. Elton and Green provide an excellent comparison of the GovPX data with other data sources on U.S. Treasury securities markets.

3.2 Data description

To give a perspective on the total size of the data set, part of that we are using, the total number of observations is 40 million (or more than 50,000 per trading day). 67% of them are firm double sided quotes. The total number of recorded trades is 2.8 million (3800 per trading day). The total volume of trading is more than 28 trillion dollars (37.5 billion dollars per trading day). The description of the data set, including the definition of variables used in this paper, and the process for cleaning the data is developed further in Appendix A.

We use a subsample of the GovPX data set for 750 trading days between 3rd January 1995 and 31st December 1997. Over this period, the data set is substantially cleaner than earlier data sets for 1991-94. We focus only on firm double sided quotes, i.e., where both bid and ask prices are provided. These quotes are more reliable in the sense that a dealer commits to consummate a trade at these quotes.

[13] In the absence of a real-time bid and offer, GovPX publishes a proprietary indicative price named Real-Time Security Valuation Price. These prices are not used in this study. See the discussion below.

3.3 Some Potential Caveats

It should be taken into account that this data set has several possible weaknesses. First, the data come from five out of six interdealer brokers, the sixth, Cantor Fitzgerald Inc., being the largest. This is not an important drawback since we would expect all major dealers subscribing to all interdealer brokers would use any mispricing, hence "equalizing different screens". This, however, may be slightly more important if interdealer brokers tend to specialize in certain segments of the market.

Second, the data set consists only of trades and quotations put through interdealer brokers. All activity between dealers themselves and between dealers and their clients remains out of scope of the data. This is unlikely to be an important concern for our study. The rationale behind that is that it could be a matter of significant concern if dealers have sufficiently different private information inflows and strategically exploit their information. Then, the choice between trading anonymously and revealing identity becomes a strategic choice. However, there is essentially no private information about matched securities.

Third, since only "innovative" quotes are recorded, the bid-ask spreads are narrower than those of individual dealers. If the depth of quotes is small enough, this would tend to underestimate the bid-ask spread.

Fourth, since the interdealer market is anonymous, it is impossible to trace the origins of quotes and trades and reveal which of them are made by the same dealer.

3.4 Methodology

U.S. Treasury bills and notes are quoted using different conventions. For consistent analysis we convert all quotations into invoice prices, i.e. the prices the investor will have to pay as a result of a transaction (excluding direct transaction costs, such as a commission to an interdealer broker), and then into an annualized yield. Bills are zero coupon instruments quoted at an ask and bid discount rates, d_a and d_b, respectively. The day count convention is actual/360, so the invoice price of a bill with payment at maturity of \$100 is

$$P_i = 100\Big(1 - \frac{(T-t)d_i}{360}\Big),\ i = a, b \tag{1}$$

where T is the maturity day (or the first business day after the maturity day, if the latter falls on a weekend or holiday) and t is the settlement day.

Notes pay coupons semiannually. Semiannual convention implies that with less than six months (after the last coupon date that occur before the maturity) to maturity notes become zero-coupon securities, paying a principal amount of \$100 and a coupon payment at maturity. They are quoted in clean prices per \$100 par amount, i.e. without accounting for the coupon payment, accrued since the last coupon payment. Therefore, the price of a note is $P_i = CP_i + AC,\ i = a, b$, where CP is a (flat) clean quoted price and AC is accrued interest. The day count convention for calculating accrued interest is actual/actual. Depending on the month of maturity, the period between the next and the last coupon dates is either $N = 181$ (182 in leap years) or $N = 184$. Therefore, the invoice price of a note is

$$P_i = CP_i + \frac{c}{2}\frac{N-(T-t)}{N},\ i = a, b \tag{2}$$

where c is an annual coupon payment per \$100.

We then convert these prices into an annualized yield, using formula[14]

$$y_i = \Big(\frac{100 + \frac{c}{2}}{P_i}\Big)^{\frac{365}{T-t}} - 1, \tag{3}$$

where c is zero for bills.

3.5 Sample Selection

In our study we match notes with notes as well as bills with notes maturing on the same day. We match Treasury notes maturing on the same day. Notes with initial maturity of

[14] Market participants use a slightly different method of comparing yields between bills and notes, namely bond equivalent yield estimation. Therefore, all decisions are taken based on that yield. We use another method, since it enables us to (1) calculate difference more precisely, because bond equivalent yield uses some simplifying assumptions, (2) compare the results with Amihud and Mendelson (1991), who use the same yield estimation method. We are unaware of the yield definition that was used by Kamara (1994). All estimations have been done also in bond equivalent yields (not shown here). All results (including the quantitative results about the yield difference) are robust to this change.

two and five years are issued monthly and mature on the last day of each month. Thus, on any given day, there are six pairs of these notes outstanding, maturing exactly on the same day within the next six months. Furthermore, notes with initial maturities of three and ten years are issued quarterly and mature on 15th day in February, May, August, and November. Therefore, on any given day there are two pairs of these notes outstanding.

Based upon the width of bid-ask spreads, (see next subsection) we identify five-year notes as being less liquid than two-year notes and ten-year notes as being less liquid than three-year notes. For each firm double-sided less-liquid note quote in our data set (where both bid and ask prices are given) we are looking for quotes of a different note with the identical maturity. If such quotes are found, the closest one to the time of the quote for less liquid note is chosen. If there are a few identical note quotes within a minute, only one is used.[15] All pairs of quotes more than 30 minutes apart are omitted.

While matching bills and notes, we pair only those maturing exactly on the same day. Our data set is large enough to allow us to perform such procedure.[16] One of advantages of our procedure is that it does not assume that any other potential market imperfection affect two bills in exactly the same way. This could be essential, if for instance one bill is on special. The discussion below also suggests this is important when one bill is on-the-run. At the same time this reduces the number of matched series, since bills always mature on Thursdays and notes either on the last or on 15th day of month. To find a particular pair, we employ the same procedure that was used match notes, where more actively traded notes were replaced by bills.

Our final sample consists of 33,388 pairs of two and five-year notes, 11,375 pairs of three and ten-year notes, and 25,858 pairs of bills and notes.

[15] This usually happens due to the on-going process of trading, where other parameters such as depth may have been changed.

[16] To match bills and notes Amihud and Mendelson (1991) straddle two neighboring bills, assuming local linear term structure patterns. Thus, they compare a particular note to a portfolio of two bills weighted depending on their maturity. The disadvantage of this method is that for very short term maturities term structure may behave in a jerky way.

3.6 Summary Statistics

We focus on U.S. Treasury securities with less than six months to maturity remaining during the period 1995-1997. Table I provides descriptive statistics of the size and depth of several segments of this market. In this maturity range, the market for bills seems to be far more active than that for notes. This holds for the number of firm double sided quotations per trading day (2500 for bills vs 650 for notes) and the daily trading volume ($256 and $40 million, respectively).[17]

Bills themselves are very heterogeneous. Bills that are on-the-run, i.e. the most recently issued in its maturity type securities, are the most active. On any given day, there are exactly two on-the-run bills, with maturity 13 and 26 weeks at the day of issuance (three and six-month respectively).[18] The number of quotes for on-the-run bills is over seven times than for off-the-run bills (i.e., all other bills) and the number of trades and trading volume is ten times higher. This suggests that market activity declines very rapidly with maturity. Further evidence is provided by Figure 1, that plots the number of firm double sided quotations for bills against their remaining maturity. The market activity is very high for approximately one week after the issuance of six month bills. It then declines very rapidly and remains stable until the same bill is reissued at three months to maturity, where the similar situation occurs. The small cyclical fluctuations in the number of quotations reflect the fact that bills are always issued every Thursday, therefore there are some weekly seasonal patterns. The results for dependence of both number of trades and trading volume on maturity are exactly the same.

Among notes, two-year notes are the most actively traded instrument by all the measures, while five-year notes tend to be the least active.[19] Comparing two-year issues with

[17] One reason for this difference is the pattern of issuing cycles. There can be up to 26 bills outstanding at the same time, while there can be only up to 20 notes outstanding. Also, being short-term instruments, bills are issued recently and not yet locked away in the investors portfolios. Notes, being more liquid than bills at the time of their issuance, are locked away by the time they have less than six months to go.

[18] The current practice for issuing bills is that every six-month bill is reissued (by means of assigning the same CUSIP to newly issued security) in three months as a three-month bill. Thus, auctions of three-month bills could be viewed as an analogue of seasoned equity issues.

[19] Interestingly, five-year notes are the most active while they are on-the-run, comparing with all other on-the-run securities.

five-year issues we see that the former are roughly three times more active. The same comparison shows that three-year notes are twice as active as ten-year notes.

Another important characteristic of the market is the size of transactions. The average size in the bill market is generally around $20 million per trade, while it is twice smaller for notes.[20] The last column in Table I shows that the duration (that is equal to the remaining maturity for discount instruments) is roughly stable across different notes.

The bid-ask spread is a well established measure of liquidity and transparency in financial markets. Table II gathers information on bid-ask spreads for all securities. Bid-ask spreads are given in basis points of annualized yield, as defined by formula (3). For instance, based on all firm double sided quotations, the average bid-ask spread for three-year notes with 40 and 80 (actual) days remaining days to maturity is 3.905 b.p. or approximately 0.65 cents per $100 trade. All means given are statistically significant at the 1% level.

The statistics for the pooled observations on bills and notes are reported in columns 1 and 2 respectively. The spread is significantly larger for notes than for bills, 4.047 versus 1.444 b.p. This is robust to considering all different maturity periods. Consider, for example, period with 40 to 80 days before maturity. The bid-ask spread is 1.676 b.p. for bills (or about 0.28 cents per $100 trade). Recalling the typical trade size from Table I, the bid-ask spread is $560 for one typical trade. Looking now at notes, the spread for an average trade size is roughly $670. It demonstrates that the difference in prices per trade is not so distinct. While the bid-ask spread may be two and half times larger for notes, the substantially large trade size for bills compensate the bid-ask spread difference. Market makers could account for the typical trade size they are facing in this market by means of adjusting the bid-ask spread.

Comparing bid-ask spreads for bills and two-year notes within maturity segment 120-160 days, we see that bills have smaller bid-ask spreads. This is surprising since looking at Figure 1, it is evident that bills are substantially less actively traded than corresponding

[20]This could be explained partially by a different clientele base: short maturities (money market) instruments and medium maturity instruments are locked in different portfolios. On the whole, the relatively big size of transactions may serve as an additional evidence about the lack of private information in this market, since if it were the case, dealers would be unwilling to reveal it through the large transactions.

notes. An institutional structure of the market can account for a substantial increase in notes spread: they are quoted with a tick of 0.391 cent per $100 trade size. This tick accounts up to 1 basis point for this maturity region. Furthermore, this difference increases sharply as maturity approaches. Therefore, the difference between bills and notes' bid-ask spreads overstates the actual difference. This implies that bid-ask spread need not be a reliable measure of market activity. Another observation that may be made looking at notes is that bid-ask spread tends to increase steadily as the maturity day approaches, and, even more, this relationship is significantly convex. One explanation is that realized spreads in price space tend to decrease with maturity and the relationship between price and yield is not linear.[21]

The maturity structure of bid-ask spreads for bills provides clear evidence of how activity (frequency of quotations, for instance) and trading volume in the market are important in determining the level of spreads. Since on-the-run bills are far more active than off-the-run ones, we would expect bid-ask spread to be smaller for them. This is indeed the case. The on-the-run three-month bill is placed in the $80 < m < 120$ category, and its bid-ask spread is 0.689 b.p., compared with 1.470 b.p. for bills with 120 to 160 days to maturity. Not reported in the table, the average bid-ask spread for only on-the-run three-month bills is 0.623 b.p.. A similar picture could be seen with the six month bills.

Importantly for the rest of the paper, the bid-ask spread varies substantially across different notes. Looking at overall mean, two-year notes have lower bid-ask spread than all other notes, while three-year notes have lower bid-ask spread than five, seven, and ten-year notes. This ranking holds for any period and also robust if we consider other measures of liquidity (trading volume and number of quotes).

[21] Another potential reason is that dealers try to get a fixed profit from each transaction, therefore increasing spreads substantially as maturity approaches.

4 Empirical Results and Discussion

4.1 Matched Notes

This subsection, we test the illiquidity premium hypothesis by matching notes of different initial maturity. In particular, we match two and five-year notes, and three and ten-year notes, maturing exactly on the same day. Table II shows that the difference in bid-ask spread between two and five, and between three and ten-year notes is of the positive sign and significant for *any* time to maturity.

Table III provides information about both the yield and price differences in matched notes. Overall, there are about 44,000 observations. All notes matured during the period 1995-97 are represented. Consider matches of five and two-year notes. The difference between bid yield of five-year notes and and bid yield of two-year notes ("bid-bid" difference) is 0.444 b.p., while the difference between ask yield of five-year notes and ask yield of two-year notes ("ask-ask" difference) is -1.238 b.p. This would amount to $110 and $300 for a typical $10 million trade. This is substantially smaller than the typical bid-ask spread on these securities. This suggests the existence of some minor discrepancy in pricing. We would expect this from the very fact of the difference between bid-ask spreads. Note, however, that only 56% of "bid-bid" difference observations are positive and 72% of "ask-ask" difference are negative, indicating that many pairs violate the basic implication of the hypothesis. The results are essentially the same for the comparison of three and ten year notes.

Still, the comparison based only the "ask-ask" and "bid-bid" differences is unsatisfactory since the difference may be caused both by the difference in *true* asset prices (that would support the hypothesis) as well as by wider bid-ask spreads for less liquid notes without affecting the effective bid-ask spread as measured by the mid point of the bid-ask spread. In other words, it could be the case that although yield differences are positive, the average price realized would be the same for both securities, if, for instance, mid point of two bid-ask spreads coincides and the number (volume) of transactions at bid price is the same as at ask price. One can model this effect in line with Roll (1984). In order to separate these two effects we decompose "bid-bid" differences between less liquid notes

(H) and more liquid notes (L) as

$$y^L_{bid} - y^H_{bid} = (y^L_{bid} - y^L_{ask}) + (y^L_{ask} - y^H_{bid}).^{22}$$

The first term is the bid-ask spread for less liquid notes, while the second is the difference between quoted ask yield for a less liquid note and quoted bid yield for a more liquid note ("ask-bid" difference). We call the second term "an intuitive measure of an arbitrage opportunity". The rationale for such a terminology is that it would indicate an existence of an arbitrage opportunity in a well-functioning market. If two securities provide the same cash flows but the intuitive measure of arbitrage is positive, then market participants could establish a short position in the more expensive security and purchase the cheaper one, thus offsetting their payoffs at maturity date and gaining an immediate profit. In other words, if two securities are priced significantly differently enough, we expect this difference be positive. It is only an intuitive and a rough measure, since it excludes from consideration such realistic features as transaction costs associated with trade and different trade sizes. If this measure is substantially negative, on the other hand, that would indicate no significant difference in pricing (as predicted by the theory).

We find that "ask-bid" is *negative* at -4 b.p. (or roughly 1 cent per $100 trade size) for two types of notes. This is substantially higher than both "bid-bid" and "ask-ask" difference and comparable to the notes' bid-ask spread. It demonstrate that the large part of the difference is due to the wider spreads for less liquid notes and not due to the difference in the assets values.

The analysis in this subsection does not support the illiquidity premium hypothesis. We do not find any significant difference between the prices of matched notes. This is a surprising result since earlier studies find a substantial "bid-bid" difference between the prices of matched bills and notes. Therefore, in the following subsections we reconsider this evidence by matching bills and notes. In particular, we are interested in comparing not only "bid-bid" difference, but also "ask-bid" difference for bills and notes.

We should stress that matching notes has a number of advantages over matching bills and notes. First, each note has its counterpart with exactly the same maturity date,[23]

[22] One might also decompose "ask-ask" differences as $y^L_{ask} - y^H_{ask} = (y^L_{ask} - y^H_{bid}) + (y^H_{bid} - y^H_{ask})$ to get the same results.

[23] Seven-year notes are issued quarterly, but have different cycle. U.S. Treasury used to issued five and

so there is no loss or bias in sampling data. Second, there is no evidence of notes being on special in this maturity range. A security is said to be on special if a premium is charged for borrowing this security in the repo market over the general collateral rate. Third, though difference in coupons may lead to discrepancies in tax treatment of the notes, it is on a much smaller scale than for bills and notes, since bills have effectively zero coupon. Fourth, notes are more homogeneous since none of them are on-the-run during the maturity range we study. Overall, the procedure of matching notes may allow to disentangle those market imperfections that could spoil the liquidity factors and concentrate on "pure" liquidity effect. The importance of these features for the bill-note comparison is investigated in the following subsections.

4.2 Matched Notes and Bills

In this section we compare the pricing of bills and notes matched by time to their maturity. Table IV provides general results of this exercise. The average difference between ask yield on a bill and ask yield on a note is 10.2 b.p. in annualized yield for the total sample. While being significantly smaller than Amihud and Mendelson (1991)'s 43 b.p. and Kamara (1994)'s 34 b.p., this difference is both statistically and economically significant, with nearly 93% of all differences being positive. This difference is not directly comparable with Amihud and Mendelson's result, since we do not use the first 30 days to maturity. If we include these observations, the difference between ask yields increases to 16 b.p. There could be a few reasons why our results are smaller than those of Amihud and Mendelson and those of Kamara.[24,25] First, they study the market in late seventies and eighties.

$2\frac{1}{2}$ months notes, so they coincide with three and ten year notes. There are just a couple such notes in our data set, therefore we are not using them.

[24]We are unaware of the exact procedure Kamara used to estimate the difference, however, this should not affect the estimation in any significant way. Since Kamara used bills with only 14 weeks to maturity, we suggest the overall difference (for all maturities) would be larger than in Amihud and Mendelson.

[25]Amihud and Mendelson use daily quotes from one particular primary dealer collected at the end of the trading day. The quotation times for matched bills and notes could be substantially different, since for not very active instruments dealers may rarely reconsider quotes and stale quotes are quite possible. We use intraday data, combining quotes of all primary dealers, therefore the period between matched quotes is usually within one hour or less. We also compare the best quotes across all dealers. While this obviously narrows the bid-ask spreads we report, this may result in increase as well as in decrease of yield

Since the period we consider is 10-15 years later, the market could have evolved, allowing more efficient dissemination of information. Second, bills and notes may be subject to differential tax treatment. The Tax Reform Act 1986 effected the tax implications for pricing bills and notes, effectively decreasing the potential difference between them. Note that all notes used in our study issued after 1985; therefore all of them are treated according to the same tax system.[26] Note, that other things being equal, the illiquidity premium hypothesis could explain why our result is smaller only if the *relative* bid-ask spread for bills with respect to notes decreased.

The "bid-bid" difference is similar at 11.5 b.p. Proceeding as in the previous section we decompose "bid-bid" differences between bills and notes as

$$y_{bid}^{note} - y_{bid}^{bill} = (y_{bid}^{note} - y_{ask}^{note}) + (y_{ask}^{note} - y_{bid}^{bill})$$

.

The results reported in the second column in Table IV indicate that the average "ask-bid" difference is 7.7 b.p. or 2.1 cents per $100 trade size, with 81.6% observations being positive. Based on a transaction size of $10 million, this would amount to a $2100 difference. The economic significance of such a difference is demonstrated by comparison with bid-ask spread, the main source of making profit for market makers, that is around $650 (see section 3.6).

We have shown therefore, in line with previous studies, that there is a significant variation in pricing between bills and notes, bills being far more expensive than notes.

These results demonstrate profound difference between matching notes and notes on one hand, and matching bills and notes on the other hand. First, both "bid-bid" and "ask-ask" differences are very significant for bills and and notes, while very small for notes and notes. Second, an intuitive measure of arbitrage opportunity is more than 7 b.p. for bills and notes, being substantially *positive*, while the same measure is -4 b.p. for

difference between securities.

[26]Tax implications on the pricing of U.S. Treasury securities are quite complicated. For our purposes in this paper it is important only that bills and notes are taxed differently and bills are usually "tax-preferred" securities over notes. For a general impact of the Tax Reform Act 1986 on U.S. Treasury Securities pricing see an excellent analysis in Green and Odegaard (1997). See also Dermody and Rockafellar (1992) and Ronn and Shin (1991) for further analysis.

notes and notes, substantially *negative*.

4.3 Cross-Sectional Pricing Differences

To understand why there is such a crucial difference between the results of the two tests (matching notes and notes vs matching bills and notes) we test the illiquidity premium hypothesis by comparing the bill-note difference for different types of notes. We are able to proceed since notes differ substantially in the quoted bid-ask spread (Table II). The null hypothesis is that for (1) notes with larger bid-ask spread the pricing difference is larger; and (2) the relationship between pricing difference and bid-ask spread is concave.

Table IV reports the results of this exercise. The pricing difference between bills and notes is significantly positive for all types of notes, deepening the result of the previous subsection. Furthermore, an intuitive measure of arbitrage is also positive for all subsamples, with about 80% positive observations for each group. At the same time, there are substantial variations across these differences (measured by "bid-bid","ask-ask" and "ask-bid" differences). For instance, two, three and ten year notes have "bid-bid" difference of about 9-10 b.p., while five and seven year notes have 13-14 b.p. Also, two and five year notes have "ask-bid" difference of more than 8 b.p., while three and ten year notes have less than 6.4 b.p. The difference between these two pairs is significant at the 1% confidence level. Patterns of "ask-ask" difference resemble those of "ask-bid". These results do not support the illiquidity premium hypothesis, since we showed that two and three year notes are the most actively traded, while five and ten year notes are relatively non active. In other words, the ranking of pricing differences between bills and notes is substantially different from the ranking of notes by different liquidity measures, including bid-ask spread. While there could be many reasons for these mismatching, this test clearly demonstrates that it is imprecise to test the hypothesis based on the pooled observations of all notes.[27]

[27] One possible explanation could be that bills matching two and five year notes are on special, while those matching three and ten year notes are not, producing thus an additional premium of roughly 3 b.p. Institutional structure of the market supports this hypothesis. Two and five year notes mature on the last day of each month. Bills futures contracts also mature on the last day of each month four times a year. Since only on-the-run three-month bills can be provided in the settlement of these contracts, off-the-run six-month bills that will be on-the-run three-month during expiration of futures contract tend

We conclude this subsection by noting that this result does not reject the hypothesis; it merely shows that there are some other factors affecting the pricing difference between bills and notes; therefore, this test may prove to be imprecise instrument to test the illiquidity premium hypothesis.

4.4 Spreads for On-the-run and Off-the-run Bills

In this subsection we try to understand further the difference between the results of the two tests (matching notes and notes vs matching bills and notes) by dividing all observations for matched bills and notes into two groups: in the first group bills are on-the-run, while in the second group they are off-the-run. As figure 1 demonstrates, bills are very heterogeneous, the main difference being between on-the-run and off-the-run bills. Indeed, liquidity is substantially higher for on-the-run bills (recall Table II). The illiquidity premium hypothesis assumes that the current bid-ask spread represents the premium demanded by the buyers to account for their *future* transaction costs. Note that the pattern depicted in Figure 1 is very stable over time: on-the-run bills are *always expected* to be very liquid, while off-the-run bills are *always expected* to be illiquid with relatively stable bid-ask spreads given time to maturity. Therefore, by distinguishing between matches where a bill is on-the-run or off-the-run, we may at the same time incorporate expectations about future bid-ask spreads in the analysis. In order to control for the time to maturity, we consider three-month (13-week) on-the-run bills and compare them with matches where bills are either 12 or 14-week. According to the hypothesis, we would expect difference between pricing difference for on-the-run bills and off-the-run bills be nonnegative.

Table V reports the results of this comparison. Contrary to the illiquidity premium hypothesis, the difference decreases substantially when we consider the pooled observations for all note types. The yield difference between matched bills and notes (measured in terms of "ask-bid") is 1.5 b.p. for on-the-run bills and about 5 b.p. for off-the-run

to be on special during the whole their life. One may check this hypothesis if combine secondary market prices data with repo rates data (the latter are unavailable to us). See Sundaresan (1994) and Duffie (1996) for a description and competing explanations of the existence of special repo rates.

bills. All results are significant at the 1% level.[28]

This surprising finding implies in line with the result in the previous subsection that matching between bills and notes do not provide the coherent testing of the hypothesis. Overall, our results imply that matching notes with notes provide more coherent test of the illiquidity premium hypothesis than matching bills with notes. To summarize, there a few reasons for that. First, market for bills is very heterogeneous, with some bills differ substantially in their liquidity characteristics from other bills. This spoils the test. Second, as was mentioned, there are still some differences in tax treatment for bills and notes even after the Tax Reform Act 1986; though presumably small, these differences may be an important factor driving short-term instruments pricing. Third, bills and notes are quoted using different tick sizes that could have a substantial effect for fixed income securities with short maturity and make bid-ask spread observations noisier and unreliable. Moreover, this may have an impact on the maturity analysis of the pricing difference and bid-ask spread. Fourth, trade size of an average transaction seems to be twice as bigger for bills than for notes; this may contribute to the difference in bid-ask spread, if, for instance, dealers aim to recover a constant profit from a trade. The presence of these and other factors will also bias the result if one matches a note with a portfolio of bills maturing in approximately the same period, since market imperfections may affect two bills constituting a portfolio in different ways.

Matching notes and notes is free of shortcomings established above.[29] Establishing that there is no significant pricing difference between matched notes we obtained two results. First, based on that evidence and our sample, we reject the illiquidity premium hypothesis. Second, it means that other market imperfections (that may include taxes, short-selling constraints and specialness, among others) may underlie the difference between bills and notes.

[28] Table V also reports the results for the different types of notes. It demonstrates that while for 4 out of 5 types of matched notes the on-the-run difference is substantially smaller, for seven year notes it differs significantly. There is only one seven-year note that is matched with bills and the period covered in the table for that note is October 1997. Thus, it appears that *current* liquidity factors may affect the asset pricing in the case of extreme events.

[29] There still could be a small difference in tax treatment for notes due to different coupon rates.

5 Conclusion

This paper argues that matching bills and notes employed by some important recent studies do not provide a coherent test of illiquidity premium hypothesis since other market imperfections such as difference in bill-note taxation, short-selling constraints and specialness may effect the overall result. Moreover, bills and notes are quoted using different tick sizes, and the trade size of an average transaction seem to be twice as bigger for bills than for notes.

This paper proposes instead matching different types of notes, with different initial maturity but with the same maturity remaining, thus providing the same cash flows. This method is free of shortcomings of the method used in the previous literature and also has some additional advantages, for example since each note has its "counterpart" in this maturity range, there is no loss in data, when matching procedure is based on exactly maturity matching. In a nutshell, the procedure of matching notes may allow to separate a few market imperfections and concentrate on "pure" (or "direct") liquidity effect. We find no substantial difference in pricing. Thus, results do not support the illiquidity premium explanation of the pricing effect of liquidity.

While different markets differ quite substantially in their organization, we may expect identification of factors causing deviations in pricing in one market could provide a substantial help in explaining a potential anomalies in other markets. An important aspect of our results still needed to be elaborated is that they prompt to analyze carefully the liquidity factors in other markets and especially the interlink between liquidity-based market imperfections, and reconsider the role liquidity factors play in asset pricing.

Appendix A GovPX Data Set

The data set comes from GovPX (website www.govpx.com) and covers the interdealer broker market for U.S. Treasury securities from 3 January 1995 till 31 December 1997. Data come in files, where each file contains observations for one trading day.

Each observation stands for firm or indicative quotation and consists of up to 29 variables. Table VI shows those inputs that have been used in this study.

The following two-stage filtering procedure was employed to obtain the final data set.

At the first stage data for securities with less than six months to maturity was chosen conditional on certain characteristics. Second stage consisted of searching for outliers.

At the first stage the following has been done:

— All observations for securities with less than 185 (actual) days to maturity were chosen. Actual days to maturity is the difference between maturity date and trading day for security.

— Among these only observations with firm bid and firm ask quotations were used (this was performed by choosing observations where firm bid price and firm ask price are both positive (zero in bid price (or ask price) means that there is an indicative bid (or ask) price that is given by another variable). Variables *bidprice* and *askprice* were used.

— Since notes pay semi-annual coupons, all those observations that contain notes with yet not paid coupon were eliminated (this could occur, since coupons are paid on calendar days and actual difference may be a bit smaller because of, for instance, February effect). Thus, only zero-coupon securities remained.

— All when-issued observations for three and six month bills have been deleted. The variable *type* was used for this purpose. On some occasions there is an incorrect input in this variable, therefore for bills with corresponding maturities it was checked manually. We are left therefore only with on-the-run and off-the-run bills.

— All observations for securities with initial maturity of more than ten years (mainly thirty year bonds) were excluded.

All prices from remaining observations have been calculated according to section 3.4. At the second stage the following outliers have been checked for and eliminated:

— Obtained yields for securities should be no less than 350 basis points and no more than 1500 basis points. This values have been chosen by looking at term structure movements of the short end of the curve. This eliminated about 0.01% of observations.

— There are some occurrences where bid-ask spread is negative. It is possible, that a stale quote was not cleared by a contributing broker or a mistake in the data, but within the filter range, applied by GovPX system, may have been given to the system by a broker. This is especially often for very illiquid securities. All such observations have been deleted, they account to 1.6% of the observations. Observations with zero bid-ask spread could occur, since only one side of transaction pays the transaction fee.

— Unreasonably high bid-ask spreads (exceeding 50 basis points) have been deleted. This accounts to 0.1% of the data.

Finally, while matching securities we discarded observations with less than 30 days to maturity left since interest rate behave quite jerky in this range.

As there is inevitably some subjectivity in choosing the boundaries to exclude outliers, the robustness checks have been run for different boundary values (yield low range: 200, 400 basis points, yield high range: 1000, 1200 basis points, high bid-ask spread range: 30, 70 and 100 basis points). No results have been affected in any serious way.

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Table I

Descriptive Statistics

Descriptive statistics on the overall market activity for U.S. Treasury securities with less than six months to maturity remaining is summarized. The sample period is from 3 January 1995 to 31 December 1997, 750 trading days in total. On-the-run bills represent the most recently issued three and six month T-Bills. n year notes represent those securities which at issue had maturity of n years. *Quotes Total* stands for the number of firm double sided quotations per trading day. All other variables are per trading day per security. *Quotes* is the number of firm double sided quotations. *Trades* provide the number of trades. *% Obs.* show the percentage of trades of firm double sided quotations. *Volume* is the trading volume in million dollars. *Size* is the average size of one transaction in million dollars. *Maturity* is the average maturity in days. The procedure for filtering the data set is described in Appendix A.

	Quotes Total	Quotes	Trades	% Obs.	Volume	Size	Maturity
Active bills	941.97	471.62	70.70	14.94	1585.87	22.43	133.73
Non-Active bills	1585.49	66.47	7.78	11.69	155.68	19.81	84.21
Total Bills	2518.23	97.41	12.26	12.94	256.99	20.97	103.26
2-year notes	341.58	56.89	5.54	9.68	66.96	12.09	96.69
3-year notes	97.23	48.74	4.59	9.29	48.26	10.53	93.22
5-year notes	119.62	25.19	2.08	8.39	17.65	8.73	93.49
7-year notes	52.38	25.79	2.34	8.85	22.81	9.69	90.11
10-year notes	37.38	22.70	2.28	8.57	23.96	10.25	88.96
Total Notes	650.13	39.58	3.66	9.26	40.37	11.02	94.59

Table II

Bid-Ask Spreads

Statistics on the bid-ask spreads for T-bills and T-Notes with less than six months to maturity left is summarized. The sample period is from 3 January 1995 to 31 December 1997, 750 trading days in total. Number of observations is given per trading day. Bid-ask spread is in basis points annualized yield. Annualized ask or bid yield, y_a or y_b, respectively, is calculated from the price P_a or P_b of security by the following method:

$$y_i = \Big(\frac{100 + \frac{c}{2}}{P_i}\Big)^{\frac{365}{T-t}} - 1, i = a, b$$

where c is a coupon rate (if any), P_i is invoice price and is the sum of clean (flat) price and accrued interest (if any). Mean bid-ask spread is given for total subsamples of each security considered and depending upon days remaining to maturity, denoted by m. Standard deviation of each sample is given in parentheses. Procedure for filtering the data set is described in Appendix A.

	bills	**notes**	**2-year notes**	**3-year notes**	**5-year notes**	**7-year notes**	**10-year notes**
observations per day	2407	650	344	99	115	53	39
bid-ask spread	1.448	4.048	3.416	3.924	4.938	5.402	5.477
	(2.939)	(6.213)	(5.662)	(5.862)	(6.646)	(7.575)	(7.398)
for $m < 40$	4.173	9.791	8.938	9.214	10.942	12.024	10.867
	(6.203)	(11.280)	(10.914)	(10.614)	(11.597)	(12.386)	(11.949)
for $40 < m < 80$	1.676	4.046	3.313	3.905	5.058	5.303	6.062
	(2.301)	(4.689)	(3.998)	(4.363)	(5.240)	(5.602)	(6.226)
for $80 < m < 120$	0.689	2.728	2.274	2.539	3.466	3.528	3.918
	(1.062)	(3.131)	(2.762)	(2.819)	(3.399)	(3.751)	(4.098)
for $120 < m < 160$	1.470	2.358	1.979	2.461	3.041	2.772	3.116
	(1.613)	(2.599)	(2.205)	(2.440)	(3.078)	(3.080)	(3.388)
for $m > 160$	0.713	2.028	1.775	1.976	2.648	2.444	2.348
	(0.908)	(2.196)	(1.989)	(2.130)	(2.553)	(2.318)	(2.535)

Table III

Differences between matched notes

This table summarizes evidence on the difference in prices between matched U.S. Treasury notes with less than 6 months to maturity. The sample period is from 3 January 1995 to 31 December 1997, 750 trading days in total. For each occurrence of a firm double sided quote (i.e., when both bid and ask prices are positive) for a five-year (ten-year) note a two-year (three-year) note with the same days to maturity left is chosen. If such does exist, then for that note the quotation occurring on the same day is chosen such that $|\tau_i - \tau_j^*| = \min[|\tau_i - \tau_j|]$, where τ is the time of a note quotation and i stands for two or three, while j for five and ten year notes respectively. All observations are pooled together. *Observations* is a total number of observations for each subsample. *Bid-Bid* stands for the difference between bid yields (prices) of matched securities, *Ask-Ask* is the same for ask yield (prices). *Ask-Bid* is the difference between the ask yield (price) for a five-year (ten-year) note and bid yield (price) for its matched two-year (three-year) note. *% positive* stands for the share of differences with positive value. The first column for each sample is yield difference and the second is difference in price space. Yield differentials are reported in basis points, while price differentials in cents per \$100. Standard deviation of each subsample is given in parentheses. Procedure for filtering the data set is described in Appendix A.

	Five vs Two year notes		**Ten vs Three year notes**	
Observations	33388		11375	
Bid-Bid	0.444	-0.112	1.208	-0.307
	(5.065)	(1.298)	(5.059)	(1.203)
% positive	0.560		0.637	
Ask-Ask	-1.238	0.307	-0.414	0.068
	(5.244)	(1.300)	(5.791)	(1.385)
% positive	0.380		0.489	
Ask-Bid	-4.074	0.996	-4.110	0.939
	(5.827)	(1.381)	(6.354)	(1.452)
% positive	0.146		0.207	

Table IV

Difference between matched bills and notes

This table summarizes evidence on the difference in prices between matched U.S. Treasury notes and bills with less than 6 months to maturity. The sample period is from 3 January 1995 to 31 December 1997, 750 trading days in total. For each occurrence of a firm double sided quote (i.e., when both bid and ask prices are positive) for a note a bill with the same days to maturity left is chosen. If such does exist, then for that bill the quotation is chosen such that $|\tau_{note} - \tau^*_{bill}| = \min[|\tau_{note} - \tau_{bill}|]$, where τ_{note} is the time of a note quotation and τ_{bill} is a vector of all firm double sided quotations for that bill occurring on the same day. All observations are pooled together. *Observations* is total number of observations for each subsample. *Bid-Bid* stands for the difference between bid yields (prices) of matched securities, *Ask-Ask* is the same for ask yield (prices). *Ask-Bid* is the difference between the ask yield (price) for a note and bid yield (price) for its matched bill. *% positive* stands for the share of differences with positive value. The first column for each sample is yield difference and the second is difference in price space. Yield differentials are reported in basis points, while price differentials in cents per $100. Standard deviation of each subsample is given in parentheses. Procedure for filtering the data set is described in Appendix A.

	All Notes		**2**		**3**		**5**		**7**		**10**	
Obs.	25858		12263		6056		4416		735		2388	
Bid-Bid	11.466	-2.989	11.419	-3.119	9.718	-2.318	14.026	-3.854	13.415	-2.911	10.804	-2.446
	(9.960)	(2.687)	(10.037)	(2.952)	(9.163)	(1.969)	(10.992)	(3.079)	(10.805)	(1.901)	(7.949)	(1.441)
% positive	0.929		0.903		0.959		0.944		0.948		0.950	
Ask-Ask	10.187	-2.692	10.855	-2.989	8.305	-1.990	12.242	-3.414	10.662	-2.378	7.586	-1.703
	(11.081)	(2.979)	(11.723)	(3.378)	(8.326)	(1.568)	(13.050)	(3.596)	(11.665)	(1.992)	(8.092)	(1.564)
% positive	0.883		0.870		0.926		0.870		0.864		0.867	
Ask-Bid	7.663	-2.035	8.150	-2.274	6.335	-1.487	9.171	-2.595	8.137	-1.837	5.597	-1.224
	(9.754)	(2.708)	(10.077)	(3.016)	(8.759)	(1.918)	(10.685)	(3.091)	(10.898)	(1.908)	(7.238)	(1.505)
% positive	0.816		0.802		0.861		0.809		0.761		0.802	

Table V

On-the-run versus off-the-run bills

This table provides evidence on the difference in pricing between matched U.S. Treasury notes and bills for two cohorts of bills: on-the-run and off-the-run. On-the-run bills are the most recently issued in three and six months maturity classes. Off-the-run are bills in neighboring two weeks. The sample period is from 3 January 1995 to 31 December 1997, 750 trading days in total. *ask-bid spread* stands for the difference between the ask yield for a note and bid yield for its matched bill. It is reported in basis points in annualized yield. *std* is a standard deviation of each subsample. Behrens-Fisher *t-stat* is a modified approximation to the test of difference between two means when variances are unequal. Procedure for filtering the data set is described in Appendix A.

	All Notes	**2**	**3**	**5**	**7**	**10**
on-the-run	1833	924	327	332	34	216
Ask-Bid spread	1.489	2.687	0.716	-0.576	7.683	-0.264
std	5.789	5.849	4.519	5.833	2.348	5.623
off-the-run	1897	809	528	271	65	224
Ask-Bid spread	4.874	6.352	4.211	7.192	3.983	4.487
std	8.683	9.830	3.841	12.639	4.362	4.556
Behrens-Fisher t-stat	14.049	9.258	11.611	9.322	-5.430	9.695

Table VI

Description of GovPX variables

Name of input	*Description*
CUSIP	Identification number of each security (CUSIP is an abbreviation for Committee for the Uniform Securities Identification Practices).
TYPE	The period of maturity cycle. Could take three values: 0 (on-the-run), 1 (off-the-run), and 2 (when-issued)
INITMAT	Maturity of security at issuance.
MATURITY	Maturity day of security.
COUPON	Annual coupon rate (takes value 0 for discount securities).
TIME	Time of the day (EST) when observation was registered. Precision is to one second.
BIDPRICE	Quoted firm bid price. Discount and when-issued securities are quoted in yields. Bonds and notes are in prices per $100 par value.
BIDSIZE	Quoted depth of the bid price. In million dollars.
ASKPRICE	Quoted firm ask price. Discount and when-issued securities are quoted in yields. Bonds and notes are in prices per $100 par value.
ASKSIZE	Quoted depth of the ask price. In million dollars.
LASTTRADEPRICE	The price of the last registered transaction for that security.
AGGVOLUME	Aggregate trading volume for that security from the start of the trading day and up to the time of this record.