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The Price of Future Liquidity: Time-Varying Liquidity in the U.S. Treasury Market ⋆

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Abstract. This paper examines the price differences between very liquid on-the-run U.S. Treasury securities and less liquid off-the-run securities over the on/off cycle. Comparing pairs of securities in time-series regressions allows us to disregard any fixed cross-sectional differences between securities. Also, since the liquidity of Treasury notes varies predictably over time, we can distinguish between current and future liquidity. We compare a variety of (microstructure-based) direct measures of liquidity to compare their effects on prices. We show that the liquidity premium depends primarily on the amount of remaining future liquidity.

1. Introduction and Motivation

Liquidity, the ability to quickly and cheaply trade an asset at a fair price, is thought to be an important element that affects the value of securities. Ever since Amihud and Mendelson's (1986) seminal work, there have been a number of studies showing that an asset's liquidity is valued in the market place.[1] These studies often compare similar securities that differ in liquidity and, with few exceptions, show that the more liquid security has a higher price or lower return.

However, it is often difficult to isolate the price premium for liquidity from other effects when comparing securities. Securities that differ in liquidity usually have

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[1] These include Eleswarapu and Reinganum (1993), Brennan and Subrahmanyam (1996), Barclay, Kandel and Marx (1997), Eleswarapu (1997), Datar, Naik and Radcliffe (1998), Amihud (2001), Chordia, Roll and Subrahmanyam (2001), and Pastor and Stambaugh (2003), who study liquidity and ex-post returns in equity markets. Amihud and Mendelson (1991), Warga (1992), Daves and Ehrhardt (1993), Boudoukh and Whitelaw (1993), Kamara (1994), Strebulaev (2002), Krishnamurthy (2002), and Longstaff (2004) study liquidity and bond yields. Silber (1991), Brenner, Eldor and Hauser (2001), and Dimson and Hanke (2002) examine other markets.

other differences that confound efforts to isolate the price effect of liquidity. For example, the less liquid security might have additional market risk or credit risk. Less liquid securities might also be subject to more asymmetric information, or they might be subject to differing tax treatments.[2] Therefore, cross-sectional studies are not able to easily distinguish liquidity effects from other security specific differences.

Additionally, while theory would suggest that expected future liquidity should affect prices, the empirical literature has almost exclusively focused on current liquidity.[3] The empirical literature has implicitly assumed that a security's current liquidity will persist over time. Though this may be a valid assumption in many cases, little is known empirically about how expected *future* liquidity affects prices.

Moreover, the notion of liquidity is itself hard to pin down. Some use the term to describe the narrowness of the bid-ask spread, but it could also refer to market depth, volume, or other measures of market activity. If traders require the ability to transact small quantities immediately, then the quoted bid-ask spread can be used to measure the price of immediate execution. However, if traders are interested in transacting large quantities quickly, then measures of depth are more important. Market participants may also be concerned about the amount of time it takes to arrange a trade. In this case, the number of daily trades, daily volume or similar measures of market activity may be more relevant. While all of these notions of liquidity are valid, ultimately our interest is in which among them most affect securities' prices.[4]

In this paper we distinguish between current liquidity and future liquidity by comparing the yields of on-the-run and off-the-run two-year U.S. Treasury notes over the on/off cycle. We relate this difference (in a time-series regression) to future trading costs, using a number of direct measures of illiquidity. This allows us to examine the extent to which each aspect of illiquidity affects prices. And by following the same securities over time, we may disregard any potentially confounding fixed cross-sectional differences between the securities.

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[2] For example, Amihud and Mendelson (1991) argue that the price difference between Treasury bills and close-to-maturity Treasury notes can be attributed to differences in liquidity. However, Kamara (1994) and Strebulaev (2002) show that there are other differences, including taxes, that affect the price difference.

[3] Exceptions include Amihud's (2001) analysis of stock returns, and Ellul and Pagano (2003) who argue that IPO underpricing is related to expected future illiquidity.

[4] Papers that study liquidity proxies in the Treasury market include Elton and Green (1998) who use trading volume as a proxy for liquidity; Fleming (1997), Fleming and Remolona (1999), and Balduzzi, Elton and Green (2001) who document intraday patterns of bid-ask spreads and trading volume; Fleming (2003) who finds that price pressure is closely related to securities' short-term price changes; and Huang, Cai and Wang (2002) who find that the number of trades is more correlated with volatility than is trading volume. Jones, Kaul and Lipson (1994) have similar results on the number of trades in equity markets. Chalmers and Kadlec (1998) argue that the bid-ask spread times turnover is the relevant measure.

U.S. Treasury securities are ideal for this type of study, since they go through a predictable cycle of liquidity and illiquidity. Two-year notes are auctioned monthly (so that at any time there are 24 issues outstanding), and the most recently issued note, referred to as being “on the run”, attracts most of the liquidity. When a newer note is issued, the older note goes “off the run” and becomes much less liquid. Because of this pattern, expected future liquidity is generally different from current liquidity, and changes predictably over time.

At the beginning of an issue cycle, the buyer of a (very liquid) on-the-run note can easily sell it during this early period to another investor who will pay a premium for the remaining liquidity. In contrast, towards the end of the cycle, although the market may still be very liquid, a buyer might expect to eventually sell the security when it is off-the-run and when there is no longer a liquidity premium. So a buyer late in the cycle should pay less of a premium since he will only benefit from a shorter time of liquidity. Thus, even if liquidity remains at a consistently high level throughout the on-the-run period, any liquidity premium in the price should decline over the period.

At each date, we measure the liquidity of the securities using various proxies (including bid-ask spreads, depth, and the overall level of market activity). Under each measure, liquidity remains high throughout the month-long on-the-run period. Shortly before the next note is issued, liquidity declines over a number of days until it reaches a new level. The note remains relatively illiquid for the rest of its life. The measure of concern, however, is the average liquidity remaining over the asset’s life. At the beginning of the issue cycle, there is a relatively large amount of future liquidity. By the end of the cycle, there is little future liquidity remaining. By comparison, the yield difference between the on-the-run note and the off-the-run note narrows over the cycle and is close to zero at the end of the month.

We find that the yield difference between the on-the-run note and the most recent off-the-run note is related to the difference in the amount of remaining future liquidity in the two securities (regardless of which liquidity measure is used). This shows that expected future liquidity, rather than just the current level of liquidity, is priced in the Treasury market.

We compare the effect of the different liquidity proxies on yields by testing which of them have additional explanatory power beyond the other measures. We find that the quoted spread and quote size are more important than the effective spread and trade size, respectively. This means that the value that investors place on immediacy – the ability to trade a quantity of securities quickly – is better measured by the quotes of market makers who supply liquidity, rather than the actual trade prices and trade sizes. However, as measures of market activity, the number of trades and volume are more related to the liquidity premium than the number of quotes.

The regression estimates allow us to quantify the effect of illiquidity on a security’s value. For example, when we measure illiquidity as the average (quoted) bid-ask spread over the remaining life of a security, we find empirically that an increase in the average spread has more than a twenty-fold effect on the yield of the note, corresponding to a marginal investor who participates in some forty trades per year. The higher yield compensates the marginal investor for all future trading costs over the life of the security.

As mentioned above, comparing a pair of Treasury notes and following them through the cycle allow us to bypass many problems that might arise if the securities are not otherwise identical. For example, if the securities we are comparing are taxed differently (which could occur due to different coupons), then there could be a resulting price difference. But as long as these differences do not vary systematically over the issue cycle, the analysis of the change in the liquidity premium over the cycle is not affected. In fact, we find significant differences in the yields of Treasury notes that do not vary over the cycle, indicating that there are other differences between the securities in addition to liquidity.

However, differences that do vary systematically over the on/off cycle could have a confounding effect on our results. For example, specialness in the repo market is known to vary with the cycle. Also, if some investors are restricted to holding on-the-run securities, a clientele effect could result that is related to the cycle. Similarly, if on-the-run and off-the-run notes have different susceptibility to liquidity *risk* (of the type considered Pastor and Stambaugh (2003)) cyclical yield differences may emerge. We test for robustness to these effects by controlling for the time since the on-the-run note was issued, and by explicitly controlling for specialness.

Our paper is related to Krishnamurthy (2002) who also examines price differences between on-the-run and off-the-run Treasuries. Krishnamurthy links the price differences to aggregate factors related to the market's preference for liquidity. In contrast, our primary focus is on how the price differences are related to measures of future liquidity, although we also find that this relation varies with proxies for the market's preference for liquidity. By focussing on direct measures of liquidity, we are also able to investigate which aspects of liquidity drive price differences.

Our study is also related to Buraschi and Menini (2002) who show that specialness of term repos is related to current and actual future repo specialness. However, we show that even when the yield difference between securities is adjusted for differences in future specialness, future liquidity is still related to the yields. This suggests that specialness in the repo market is not a reflection of liquidity in the cash Treasury market.

The rest of this paper is organized as follows: Section 2 briefly outlines the theory of the effect of liquidity on asset prices. Section 3 describes the market and the data. Section 4 gives an overview of how liquidity in the Treasury market varies over the on/off cycle. Section 5 describes the details of the methodology. Section 6 contains the empirical results and Section 7 concludes.

2. Theory of Liquidity and Bond Prices

In this section we discuss the relation between liquidity and bond prices based on Amihud and Mendelson (1986). The purpose of presenting the theory is to clarify the relation that is to be tested empirically.

Illiquidity can be generally thought of as being measured by c, the cost to sell a security as a proportion of its value. This can represent the bid-ask spread, the opportunity cost of waiting to trade, or any similar cost. Let us consider the cost borne by the seller of the security. Suppose the investor sells when hit by an exogenous liquidity shock, and let λ_i be the per-period probability of investor i being hit by such a liquidity shock.

We will first compare a fully liquid zero-coupon bond (i.e., one that has no trading costs) with a similar bond that has positive trading costs, c. We assume the existence of a risk-neutral marginal investor, m, who is indifferent between owning the two securities. This investor has a probability of λ_m of being hit with a liquidity shock each period.

The main results shown below are: (1) The value of an illiquid bond is reduced by the expected trading costs over the entire life of the asset. (2) The expected per-period proportional trading costs, $\lambda_m c$, can be viewed as a discount rate. Therefore, the yield of an illiquid bond is equal to the yield of a liquid bond plus $\lambda_m c$. (3) If two bonds have different trading costs (which may vary over time), the difference in their yields is equal to the difference in expected *average* trading costs to the marginal investor over the remaining life of the securities.

Let f_t be the one-period forward rate of interest from time $t-1$ to t for the perfectly liquid bond. Both the liquid and illiquid bond mature at time T at which time they each pay \$1.

At time $T-1$, the value of the liquid bond is (by definition):

$$P_{T-1}^{L} = \frac{1}{1+f_T}$$

and at any time t,

$$P_t^L = \prod_{j=t+1}^{T} \left(\frac{1}{1+f_j} \right).$$

At time $T-1$ the owner of the illiquid bond is no longer subject to liquidity shocks before maturity and values his bond as

$$P_{T-1}^{I} = \frac{1}{1+f_T}.$$

However, at time $T-2$, the owner of the illiquid bond will be concerned about the probability λ_m that he will be hit with a liquidity shock at time $T-1$ and will have to pay cP_{T-1}^{I}. Therefore, the value of the illiquid security at $T-2$ is

$$\begin{aligned} P^I_{T-2} &= \frac{1}{1+f_{T-1}}\left[(1-\lambda_m)\,P^I_{T-1} + \lambda_m\,(1-c)\,P^I_{T-1}\right] \\ &= \left(\frac{1}{1+f_{T-1}}\right)(1-\lambda_m c)\,P^I_{T-1} \\ &= (1-\lambda_m c)\,P^L_{T-2}. \end{aligned}$$

This is the expected value of the illiquid bond at $T-1$ (less the expected trading costs) discounted back to $T-2$. More simply, the value of the illiquid bond is equal to the value of the liquid bond reduced by the expected trading costs. Similarly, at time $T-3$, the value of the illiquid bond is

$$P^I_{T-3} = \left(\frac{1}{1+f_{T-2}}\right)(1-\lambda_m c)\,P^I_{T-2} = (1-\lambda_m c)^2\,P^L_{T-3}.$$

More generally, at any time t, the value of the illiquid bond is

$$P^I_t = (1-\lambda_m c)^{T-t-1}\,P^L_t$$

or equivalently,

$$P^I_t = (1-\lambda_m c)^{T-t-1}\prod_{j=t+1}^{T}\left(\frac{1}{1+f_j}\right).$$

In continuous time, the equation simplifies, and the value of the illiquid bond can be expressed as

$$P^I_t = e^{-\int_t^T (f_\tau+\lambda_m c)d\tau} = e^{-\lambda_m c(T-t)}\,P^L_t \qquad (1)$$

where f_t is now the instantaneous forward rate. Equation (1) can be rewritten using yields as follows:

$$P^I_t = e^{-y^I_t(T-t)} = e^{-\left(\lambda_m c+y^L_t\right)(T-t)}, \qquad (2)$$

where y^L_t and y^I_t are the yields to maturity for the liquid and illiquid bonds, respectively. Thus, the relation between the yields of the two bonds is simply

$$y^I_t = \lambda_m c + y^L_t. \qquad (3)$$

In words, the yield of an illiquid bond exceeds the yield of a liquid bond simply by the proportional trading cost times the per-period probability of a liquidity shock to the marginal investor.

The fact that $\lambda_m c$, the expected per-period trading costs, is added to the bond's yield illustrates the similarity between expected trading costs and interest rates. Just like an interest rate of r reduces a cash flow's value at a rate r per period, an expected trading cost of $\lambda_m c$ reduces a bond's value at a rate $\lambda_m c$ per period.

This analysis can be generalized to a case in which both assets are somewhat illiquid (and now denoted as assets A and B) with trading costs c^A and c^B, respectively. We assume that there exists a marginal investor who is indifferent between the two assets. In this case the relation between the yields of the two assets is

$$y_t^B = \lambda_m \left(c^B - c^A\right) + y_t^A. \tag{4}$$

Thus, the yield spread between the two bonds is proportional to the difference in trading costs.

We can further generalize to allow for the possibility of trading costs varying over time. This is particularly relevant for our study of U.S. Treasury notes, since the liquidity of notes does vary predictably over time. To do this we make a simple adjustment to Equation (1), which leads to Equation (4) being rewritten as

$$y_t^B = \lambda_m \left(\overline{c^B} - \overline{c^A}\right) + y_t^A \tag{5}$$

where $\overline{c^i}$ is the average trading cost over the remaining life of security i. In this case, the difference between yields is proportional to the *average* difference between the trading costs of the two securities. If future trading costs are uncertain, or if the probability of a liquidity shock to the marginal investor is uncertain, then an expectation operator and covariance terms must be added.

3. The Market for U.S. Treasury Securities: Description and Data

The United States Treasury sells securities by auction on a regular schedule to finance the national debt. The empirical analysis in this study focuses on two-year notes which tend to have the largest issue size of all Treasury securities. The notes are auctioned monthly, so at any time there are 24 issues outstanding. As explained above, the most recently issued security of a given maturity is referred to as "on-the-run" and older securities are referred to as "off-the-run". The on-the-run security is considered to be the benchmark security, and attracts most of the trade and liquidity.

The secondary market is predominantly an over-the-counter market with many brokers and dealers. During most of the period for which we have data, there were six major interdealer brokers who allow dealers to trade anonymously with each other.

Quotes are submitted to interdealer brokers who display them for all dealers to see. To effect a transaction, a dealer hits a bid or takes an ask that is displayed. Thus all trade occurs at quotes. However, price improvement occurs when dealers improve on each other's quotes while waiting for a counterparty.

In spite of the large number of dealers in the over-the-counter market, the vast majority of the quoting and trading activity is by less than 30 primary dealers. Primary dealers are those approved to transact directly with the Federal Reserve in its market operations and are expected to participate in Treasury auctions.

The data set on the U.S. Treasury market that is used in this study is from GovPX.[5] GovPX was set up in 1990 by all, except one, interdealer brokers in order to provide greater transparency in the U.S. Treasury market. The GovPX data set includes all trades that are transacted through participating interdealer brokers. It consists of the best bid and ask prices, trade prices, and the size of each trade and quote. There is no other data set for U.S. Treasury securities that covers a similarly extensive period of intraday quotes and trading activity.[6] For one section of this paper we also use the GovPX overnight repo indices. This data is described when we discuss the adjustments for repo specialness (in Section 6.4).

This study uses data from May 1994 to November 2000 related to all two-year Treasury notes issued from the beginning of May 1994 until the end of November 1998. During this time period, the monthly issue size for the two-year note ranged from $12 billion to $18.75 billion (with an average size of $16.8 billion and a standard deviation of $1.6 billion).

4. Overview of Treasury Market Liquidity

Examination of the various measures of liquidity and trading activity over the issue cycle of the two-year note reveals some interesting patterns. Figure 1, Panels A through D, shows how liquidity varies over the first 100 trading days of the securities' lives. We measure time relative to the issue date of each security and average over the cross-section of securities. The first 22 trading days correspond, approximately, to the on-the-run period.

Panel A shows the average daily quoted and effective spreads (in yield space) averaged across the two-year notes in our sample for the first 100 days after issue.[7] The quoted spread is the difference between the best bid and the best ask at any time and averaged over all quotes in a day. (Quotes that are not firm, but merely indicative, are excluded from this study.) The effective spread is defined as twice

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[5] Because the GovPX data set is unique in its coverage of the Treasury securities secondary market, it is important to point out a limitation. The data does not include trades and quotes routed through Cantor Fitzgerald, which has a market share of about 30%. Cantor Fitzgerald is particularly strong at the "long end" of the Treasury maturity spectrum. Our choice of the two-year note as the focus of this study was influenced by reduced data quality in the GovPX data set for longer maturity securities.

[6] Prior to the availability of GovPX, studies either used quotes collected by the Federal Reserve Bank of New York from a daily survey of dealers, or small proprietary data sets.

[7] The GovPX data reports a new quote whenever any field in the data related to the inside quotes changes, including the quoted price and quote size, as well as changes that are of lesser economic importance. We use all reported quotes, regardless of the reason for the new quote, in the average quoted spread, the average quoted depth, and the number of quotes per day,

the difference between each trade price and the most recent midquote.[8] Since, all trades occur at the quotes, the effective spread is equal to the quoted spread immediately before each trade. The average effective spread is lower than the average quoted spread because trades tend to occur after a narrowing of the spread. During the first 15 trading days the effective spread is approximately 0.4 basis points, while the quoted spread is about 0.6 basis points. Over the following week, in the run up to the issue of the next two-year note, spreads widen. The timing of this drop in liquidity corresponds to the beginning of trade in the pre-auction (when-issued) market for the next two-year note.

Bid-ask spreads continue to widen as the remaining life of the security shortens. When the security is off-the-run, the effective spread is mostly above one basis point and the quoted spread averages more than two basis points. Off-the-run spreads are considerably more volatile than on-the-run spreads.

Panel B shows the average quote and trade sizes. During the on-the-run period, quotes average about $20 million and the average transaction size is between $10 million and $15 million. In comparison, during the off-the-run period trade size averages about $7 million while the average quote size falls much further to between $2 million and $3 million.[9] Panel C shows the average numbers of quotes and trades per day. There are about 3000 quotes and 400 trades daily per security during the on-the-run period. During the off-the-run period, there are a few hundred quotes and as little as 15 trades daily. Panel D shows daily volume which ranges from over $6 billion per day during the on-the-run period to approximately $100 million per day during the off-the-run period.

5. Methodology

Our empirical analysis studies the yield difference between on-the-run and off-the-run securities and relates it to the difference in future liquidity using a variety of liquidity measures. By focussing on the time series of yield differences, we can safely ignore any fixed effects that cause the yields of the notes to differ.

Over the period of our study, there were 56 two-year Treasury notes that were issued and also matured during the time period. We group these 56 securities into 55 pairs of successive notes that were issued one month apart. We label the newer of the pair as on the run and the older as off the run. Starting from the issue date of the on-the-run security, we measure the difference in yields between the two securities each day until the on-the-run note goes off the run.

We compare the midquote yields of the two securities using tick-by-tick data. For each quote in the off-the-run note, we subtract the contemporaneous midquote

[8] Because the GovPX data aggregates quotes and trades for multiple brokers, the effective spread (as defined here) may not always equal the quoted spread at the time that the trade was initiated.

[9] Quote size should not be taken as a literal measure of market depth, since further negotiation over trade size can occur. See Boni and Leach (2004).

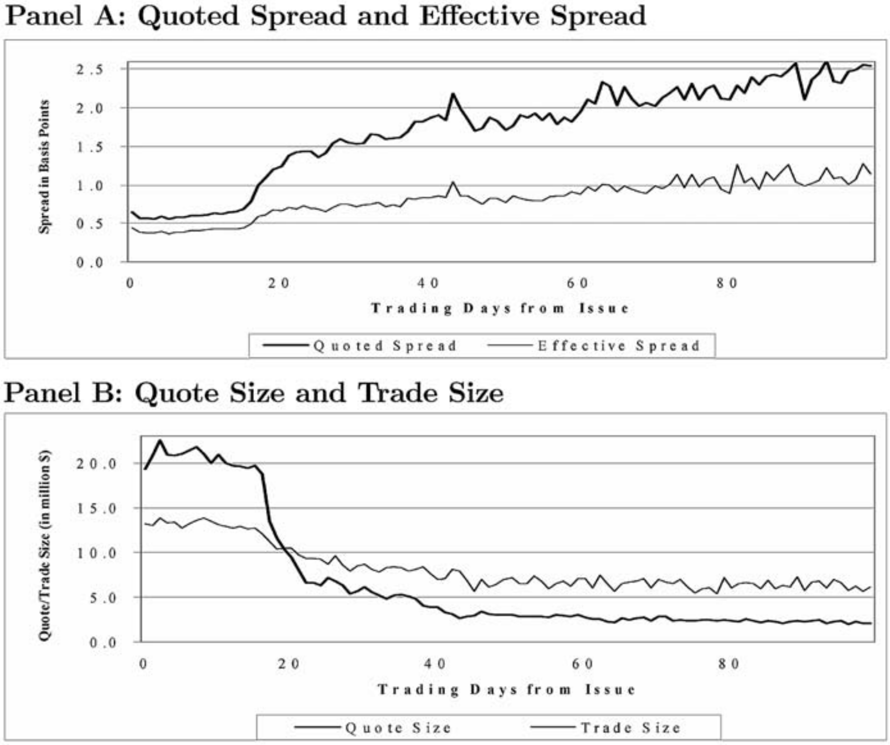


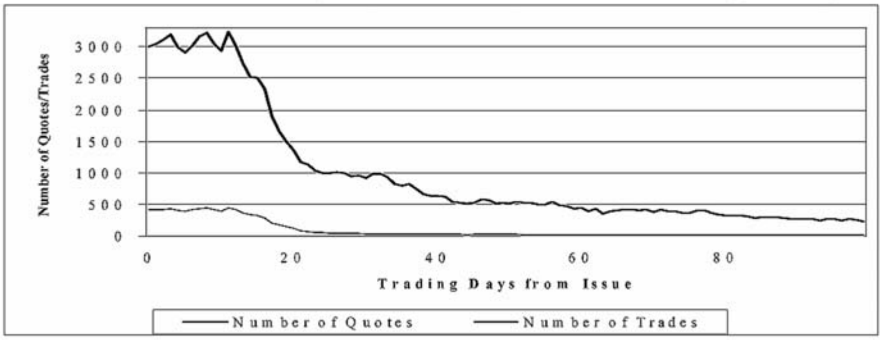
Figure 1 (Panels A & B). Overview of market liquidity. Panel A shows the average quoted spread and the average effective spread over the first 100 trading days of the two-year US Treasury notes in our sample. Both the quoted and the effective spreads are very low during the on-the-run period (averaging about 0.6 and 0.4 basis points, respectively) and considerably higher afterwards. Panel B shows the average quote size and the average trade size over the first 100 trading days. Both quote and trade size are very high during the on-the-run period (averaging about \$20 million and \$13 million, respectively) and considerably lower afterwards (averaging about \$2.5 million and \$6 million, respectively). The quote size declines more rapidly than the trade size over time. While the average quote size exceeds the average trade size during the on-the-run period, it is lower during the off-the-run period.

yield of the on-the-run note. This difference between the yields is averaged across the day to obtain the daily yield difference.

Following Amihud and Mendelson (1991), to mitigate any potential problem of asynchronous quotes, we define the contemporaneous on-the-run yield to be the weighted average of the on-the-run midquotes taken just before and just after each off-the-run quote (with weights based on the time between each of the on-the-run quotes and the off-the-run quote).[10]

[10] It is unclear whether this adjustment is necessary, since at the time of the off-the-run quote, the previous on-the-run quote is still valid. However, if there is a delay between the arrival of new information and the submission of updated quotes, then the previous on-the-run quote will be slightly stale.

Panel C: Number of Quotes and Number of Trades per Day



Panel D: Volume per Day

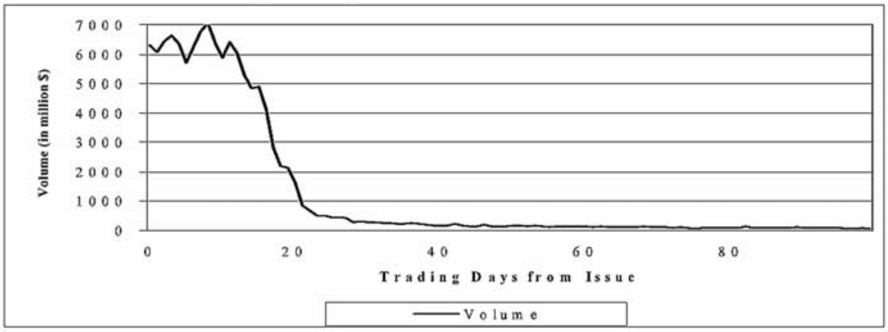


Figure 1 (Panels C & D). Overview of market liquidity. Panel C shows the average number of quotes and the average number of trades per day over the first 100 trading days. Both the number of quotes and the number of trades are very high during the on-the-run period (averaging about 3,000 and 400, respectively) and considerably lower afterwards (averaging less than 400 and approximately 15, respectively). Panel D shows the average volume per day over the first 100 trading days. Volume during the on-the-run period is extremely high compared to the off-the-run period (averaging over $6 billion *vs.* approximately $100 million). There is an abrupt decline in volume at the end of the on-the-run period.

There are two adjustments that we make to obtain a cleaner comparison. First, successive issues normally have different coupons. Since bonds with different coupons naturally trade at different yields, we make an adjustment to the yield of the off-the-run note so that it will be comparable to a note of the same maturity but with a coupon equal to the on-the-run coupon.[11] This coupon adjustment is simply the difference in yields between two hypothetical notes (of the same liquidity) both with the same maturity as the off-the-run security but with different coupons – one with the actual coupon of the off-the-run note and one with a coupon equal to that of the on-the-run note. We use zero-coupon bond price data to construct and calculate

[11] There is no qualitative difference in our results if this adjustment is not made.

the yields of these hypothetical securities to obtain the coupon adjustment.[12] For example, suppose a 24-month on-the-run note has a 6% coupon and a 23-month off-the-run note has a 5.5% coupon. We use the zero-coupon bond price data to value both a hypothetical 23-month 5.5% note and a hypothetical 23-month 6% note. For each of these hypothetical prices we calculate yields. The difference between these two calculated yields is the coupon adjustment and is added to the actual quoted yield of the off-the-run note. Any small errors in the zero-coupon data appear in the yields of both hypothetical bonds and only have a negligible effect on the adjustment.

A potentially more serious problem is that the two notes that we compare, although very close in maturity, are not exactly at the same point on the yield curve. Hence, if the yield curve is not flat we would expect them to have different yields even in the absence of any liquidity effect. We solve this problem in a manner similar to the adjustment for the difference in coupons. An adjustment is added to the yield of the off-the-run security for being of a slightly shorter maturity. The adjustment is equal to the difference between two yields: the yield of a hypothetical security (constructed from zero-coupon bond data) with a maturity equal to the maturity of the on-the-run, and the yield of a second hypothetical security with a maturity equal to the maturity of the off-the-run. Again, since the adjustment is a difference between two yields calculated using the same zero-coupon bond data, any small data errors have a negligible effect.[13]

The yield difference at each time t for each pair of notes, YD_t, is the yield of the off-the-run security minus the yield of the on-the-run security (adjusted as above) measured in basis points.

The yield difference for each day of the on-the-run period, averaged over the cross-section of the 55 pairs of securities, is shown in Figure 2. At the beginning of the cycle, it is approximately 1.5 basis points and declines toward zero over the month. This is an economically significant effect considering the leverage often found in bond portfolios.[14] Krishnamurthy (2002) finds a similar pattern, albeit of larger magnitude, for thirty-year bonds. Our task in this paper is to relate this pattern to measures of future liquidity of on-the-run and off-the-run notes.

According to the theory in Section 2, this yield difference should capture the difference between the expected lifetime liquidity of the two securities. After the yield difference is calculated for each day of an issue cycle, we relate it to various

[12] The hypothetical yields are obtained from a spline of zero-coupon bond prices. The spline excludes any strip that has a maturity close to that of the on-the-run security to bypass any liquidity premium in the zero-coupon data.

[13] As with the coupon adjustment, this yield-curve adjustment does not qualitatively affect the results. This is not surprising, as these are cross-sectional adjustments that should not vary systematically over the cycle.

[14] The extent to which this is arbitragable depends on the transaction costs of conducting such a trade and, most importantly, the cost of short selling, i.e., specialness in the repo market. In Section 6.4 we find that repo specialness only partially accounts for the yield difference between off-the-run and on-the-run notes.

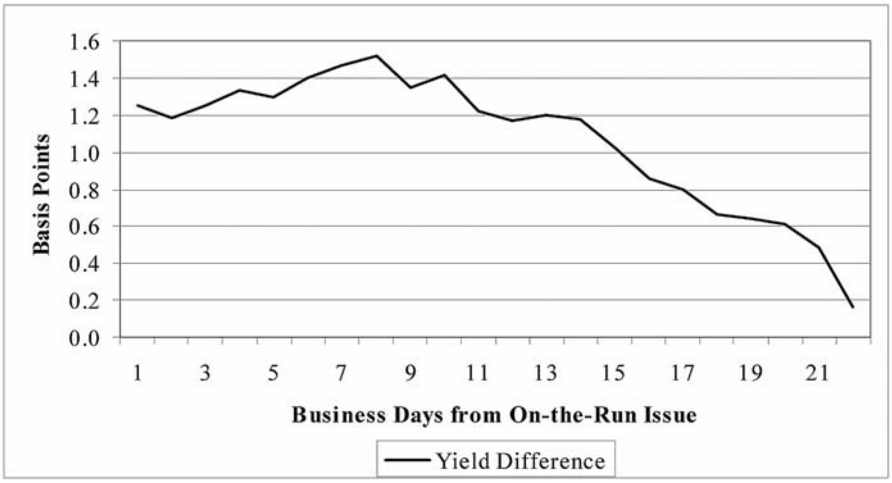


Figure 2. Off-the-run yield minus on-the-run yield (adjusted). This graph shows the average difference between the yields of off-the-run and on-the-run two-year US Treasury notes in our sample (adjusted for differences in coupon and maturity between each pair of notes). The difference in yields declines over the month until a newer note is issued.

measures of future liquidity, or more precisely, future trading costs. This allows us to show that the difference in yields can indeed be attributed to future liquidity differences and to determine which aspects of liquidity have an impact on prices.

Theory predicts that the yield of a bond is equal to the yield of a perfectly liquid bond plus a term to capture expected future trading costs. Therefore, we propose the following econometric model to capture how the yield difference between an off-the-run and an on-the-run security is related to future trading costs:

$$YD_t = \sum_{i=1}^{55} \alpha_i I_{it} + \beta \left(\overline{C}_{off,t} - \overline{C}_{on,t}\right) + \varepsilon_t \tag{6}$$

where I_{it} is a fixed-effects dummy that is set to one if pair i includes the on-the-run security at time t, and α is the vector 55 coefficients to control for any constant difference between a pair of securities. β corresponds to λ_m in the theory section – the probability per year that the marginal investor will experience a liquidity shock. $\overline{C_t}$ is the average cost associated with trading a security over its remaining life, i.e., from time t until maturity. The expectations operator is dropped from the future cost measures because (in the absence of a model of expected trading costs) we use realized future trading costs as a proxy for expected trading costs.[15] Thus, unanticipated changes in liquidity will add noise to our future cost measures. This econometric model corresponds to Equation (5) in the theory section.

[15] In Section 6.3 we introduce the time that a security has been on the run as an explanatory variable, which can be interpreted as a simple model of expected trading costs.

One should keep in mind that the cost of trading should be loosely interpreted to include any direct or indirect trading costs to a security holder such as the bid-ask spread, an inability to trade immediately or any other drawback of illiquidity. One of our objectives is to find measures of $\overline{C}$ which are most closely related to the yield difference, YD_t.

For each day we calculate the following measures of (il)liquidity:

1. the average quoted bid-ask spread (as a percentage of security value measured in basis points),
2. the average effective bid-ask spread (i.e., the bid-ask spread immediately before each trade),
3. the average quote size (in millions of dollars, where the quote size is measured as the average of the bid and ask quantities),
4. the average trade size (in millions of dollars),
5. the number of quotes per day,
6. the number of trades per day, and
7. the daily volume (in millions of dollars).

For measures (1) and (2), the trading cost, C_t, is calculated each day as the average of all bid-ask spreads throughout the day. Although the dependent variable is measured in yield space, as motivated by the theory the bid-ask spread measures are as a percentage of price. This is because the coefficient β estimates the probability *per year* that the marginal investor will experience a liquidity shock, so when multiplied by the trading cost corresponds to a yield measure.

For measures (3) to (7), which capture depth and market activity, we take the natural logarithm of the reciprocal of each measure on each day. Reciprocals are used so as to interpret them as costs, and logarithms are used because we expect trading costs to be nonlinear in these measures.

At each date t, we calculate $\overline{C_t}$, as $\frac{1}{T-t}\sum_{\tau=t}^{T} C_\tau$, the average daily trading cost over the remaining life of the security.[16]

6. Empirical Results

6.1. BASIC REGRESSIONS

In order to empirically test the relationship between the yield difference (between off-the-run and on-the-run notes) and the difference in expected future liquidity (i.e., Equation (6)), we pool the data in a panel that includes the cross-section of 55 pairs of notes and a month-long time series for each pair of notes.[17] We use

[16] Because the data for the last few months before maturity is very noisy, we assume that the costs during the last six months before maturity are the same as the average over the previous year.

[17] We cannot use a time series of longer than one month because the on-the-run security in one pair of securities becomes the off-the-run security for the next pair in the following month.

a fixed-effects panel-data model to regress the yield difference on the difference in average future trading costs, $\overline{C}_{off,t} - \overline{C}_{on,t}$, and a set of fixed-effects dummy variables (one for each on/off pair). We run individual regressions for each of the seven cost measures, as listed at the end of the previous section, using the following regression model:

$$YD_t = \sum_{i=1}^{55} \alpha_i I_{it} + \beta \left(\overline{C}_{off,t} - \overline{C}_{on,t}\right) + \varepsilon_t. \tag{7}$$

The dummies, I_{it}, in each regression are intended to isolate the impact of future trading costs from unrelated cross-sectional differences between the securities.

The fact that we are using an average of trading costs on the right-hand side of the equation introduces significant positive autocorrelation in the regression residuals. We adjust for autocorrelation in the residuals using a feasible generalized least squares (FGLS) model for panel data. (FGLS adjusts both the coefficients and the standard errors.) The regression results for the first and second month after the issue date of the on-the-run security are shown in Table I.

As shown in Panel A of Table I, for the first month, the coefficients for each of the seven future cost measures are positive and highly significant.[18] This shows that the yield difference between off-the-run and on-the-run notes is related to future liquidity regardless of which measure of trading cost we use. The fact that all of the cost measures give similarly significant results should not be surprising since they are highly correlated with each other.

If the cost of a trade is taken to be half the bid-ask spread, then twice the coefficient on the bid-ask spread is an estimate of the marginal investor's per-year trading frequency. For example, if the cost of trading is the quoted spread, then an increase in the average bid-ask spread of 0.01 basis points over its remaining life will result in a 0.22 basis point rise in yield. This reflects a marginal investor trading 44 times per year. In particular, because the individual time series are run over the first month of the new security's life (although later costs are included in C), the coefficient should be interpreted primarily as the marginal investor's trading propensity over the first month.

Because the other cost measures are not literally costs, their coefficients do not lend themselves as easily to interpretation. However, they do give estimates of the effect of liquidity on yields. For example, if average daily volume over the life of the security increases by 1%, we should expect the yield to decrease by about 0.07 basis points.

Notably, the fixed-effects dummies for each pair of securities are significantly different from each other and account for a large portion of the variation. (The coefficients of these dummy variables are not reported.) This indicates that there

[18] Since we hypothesize a positive relation between the yield difference and trading costs, the t-statistics should be interpreted in the context of a one-tailed test.

Table I. Regression of yield difference on future trading cost measures

The first column of this table shows the results of autocorrelation-adjusted panel regressions of the yield difference on the difference between the future cost measures for off-the-run and on-the-run notes (run separately for each of the seven cost measures). For each cost measure, the regression equation is

$$YD_t = \sum_{i=1}^{55} \alpha_i I_{it} + \beta \left(\overline{C}_{off,t} - \overline{C}_{on,t} \right) + \varepsilon_t,$$

where YD_t is the difference in yields between the off-the-run and on-the-run securities on date t (measured in basis points); $\overline{C_t}$ is the average future trading costs (under the various measures) from time t until maturity; and I_{it} is a fixed-effects to isolate cross-sectional differences other than liquidity. The regressions are repeated in first differences with only one intercept. Using the Fama and MacBeth (1973) procedure we also run the regressions separately for each pair of securities and average the regression coefficients. In Panel A, the regressions are run over the first month from the issue of the on-the-run security. In Panel B, the regressions are run over the second month. Autocorrelation-adjusted t-statistics are in parentheses. Partial R^2 for the panel regressions in levels are shown in the last column. These represent the explanatory power of the cost measures isolated from other cross-sectional differences captured by the fixed effects dummies. The R^2 for the regressions in differences for both the first and second months are below 1%.

Cost measure	Panel regression	Partial R^2	Panel regression (differences)	Fama-MacBeth
		Panel A: First Month		
Quoted spread	22.1 (10.8)	11.55%	27.3 (2.6)	10.7 (2.1)
Effective spread	66.8 (14.1)	11.18%	42.5 (2.2)	35.8 (2.2)
log(1/Quote size)	16.0 (8.9)	9.00%	40.5 (2.7)	9.0 (2.5)
log(1/Trade size)	43.1 (11.7)	7.44%	28.8 (2.1)	20.0 (1.8)
log(1/# of quotes)	18.1 (7.8)	7.17%	33.1 (1.6)	13.9 (2.1)
log(1/# of trades)	7.5 (8.8)	9.29%	21.6 (3.0)	4.1 (2.4)
log(1/volume)	6.6 (9.1)	9.05%	19.4 (3.2)	3.5 (2.3)
		Panel B: Second Month		
Quoted spread	0.8 (0.8)	2.91%	−1.1 (−0.6)	6.5 (1.4)
Effective spread	35.4 (4.4)	0.21%	8.6 (0.8)	1.3 (0.1)
log(1/Quote size)	5.1 (1.8)	3.80%	−16.5 (−1.8)	23.1 (2.8)
log(1/Trade size)	15.6 (4.3)	2.72%	−6.7 (−1.1)	33.9 (2.7)
log(1/# of quotes)	−0.9 (−0.2)	2.92%	−9.5 (−0.9)	56.8 (1.6)
log(1/# of trades)	−4.7 (−1.5)	0.20%	−8.0 (−1.5)	1.5 (0.1)
log(1/volume)	−0.7 (−0.4)	0.94%	−6.7 (−1.8)	5.5 (0.8)

are other effects, unrelated to liquidity, that make the yield of one note different from another.

Because of concern about persistence in the right-hand side variable, we repeat the analysis with both sides of the regression differenced along the time-series dimension which removes any first-order autocorrelation. Similar results are obtained, except that the number of quotes is of only marginal statistical significance.

Since we are running a panel regression with time series for each of 55 pairs of securities, as a further robustness check, we repeat the analysis using a variation of the Fama and MacBeth (1973) procedure. This controls for lack of independence within the time series for each pair of securities. Under this procedure, we run separate time-series regressions for each of the 55 pairs of securities. The reported coefficient is the average of the estimated coefficients, and the t-statistic is computed using the standard deviation of the series of coefficient estimates. Again, the results are similar, and all coefficients are statistically significant.

The regressions in Panel A of Table I are run over the first month after the issue of the on-the-run security. In the first month, the difference in liquidity between the on-the-run note and the off-the-run note is striking. In the second month, after an even newer security is issued, neither security from the original pair is considered on the run and the liquidity difference (and the yield difference) between them is modest. Panel B of Table I repeats the analysis for the second month after the issue of the on-the-run security.

The basic regressions in the first column of Panel B show that while some of the trading cost measures are significantly related to the yield difference in the second month, a number of the measures are not. When we difference both sides of the regression in the time-series dimension, we no longer find a relationship between liquidity and the yield difference. Under the Fama-MacBeth technique, the results are mixed.

The fact that the model does a poor job in relating the trading costs to the yield difference in the second month could be due to noisier price data in the second month, and the fact that there is a much smaller yield difference to explain.[19] However, it is also possible that the marginal investor changes between the first month and the second month. When comparing a new on-the-run note with the most recent off-the-run note, a marginal investor is one who trades frequently, values liquidity, and is indifferent between the more expensive liquid security and the cheaper, but less liquid, security. However, in the second month, since there is a newer security that attracts most of the liquidity, the marginal investor may now be one who trades less frequently, values liquidity less, and chooses between the two securities both of which are fairly illiquid. If this is the case, the regression coefficients in Panel B

[19] The difference in repo specialness also tends to be much smaller in the second month. The relation between repo specialness and liquidity is explored in Section 6.4.

should be expected to be smaller than those in Panel A.[20] For the remainder of the paper, we restrict the focus to the first month.

6.2. CONTEMPORANEOUS VS. FUTURE LIQUIDITY

We have shown above that the yield difference, YD_t, is related to future trading costs. However, the previous literature has focused almost exclusively on current liquidity. We now separate contemporaneous liquidity and future liquidity to determine the extent to which each of them relate to asset prices. We do so by calculating C_t, the trading costs measured only on date t, and $\overline{C}_{t+1} = \frac{1}{T-(t+1)} \sum_{\tau=t+1}^{T} C_\tau$, the average future trading costs over the remaining life of the security excluding the current day. In order to capture the incremental explanatory power of future trading costs beyond the current cost we orthogonalize the difference in future costs (between the two securities) relative to the difference in contemporaneous costs and the fixed-effects dummies.[21] If contemporaneous costs capture the variability in the yield difference, then the orthogonalized future cost coefficient should be statistically insignificant. This would also be true if contemporaneous costs are a good proxy for expected future costs. We test this with the following regression (run over the first month after the issue of the on-the-run security):

$$YD_t = \sum_{i=1}^{55} \alpha_i I_{it} + \beta \left(C_{off,t} - C_{on,t}\right) + \gamma \left(\overline{C}_{off,t+1} - \overline{C}_{on,t+1}\right)^{orth} + \varepsilon_t. \quad (8)$$

The results of this regression, for each of the seven cost measures, are reported in Table II.

In the second column of Table II, we see that all the future cost coefficients are highly significant indicating that future liquidity is indeed related to prices beyond that which is captured by current liquidity. Even when the variables are differenced almost all the future cost coefficients are significant. Contemporaneous liquidity has mixed (and weaker) results reflecting the fact that current liquidity is only a small part of the lifetime liquidity and thus should only have a small affect on prices. We must stress that due to the orthogonalization, any common component in contemporaneous and future costs is captured in the coefficient for the contemporaneous cost.

[20] A test of this hypothesis could have two independent variables for the difference in future trading costs - one for the first month and one for the remainder of the lives of the securities. However, when running such a test, the noise in the measures of off-the-run trading costs leads to very high standard errors for the second independent variable and an inability to draw any meaningful conclusions.

[21] The orthogonalization procedure is as follows: We regress the difference in future trading costs on both the contemporaneous trading costs and the fixed effects dummies. The residual of this regression, the component of future liquidity differences which is unrelated to current liquidity, is used on the right hand side of the regression in Equation (8).

Table II. Regression of yield difference on contemporaneous and future trading cost measures

This table shows the results of autocorrelation-adjusted panel regressions of the yield difference (YD_t) on the contemporaneous trading cost difference and the (orthogonalized) future trading cost difference for each of the seven cost measures. Fixed-effects dummies are included to control for cross-sectional differences. The regression is run over the first month from the issue date of the on-the-run security. The regression equation is as follows:

$$YD_t = \sum_{i=1}^{55} \alpha_i I_{it} + \beta \left(C_{off,t} - C_{on,t}\right) + \gamma \left(\overline{C}_{off,t+1} - \overline{C}_{on,t+1}\right)^{orth} + \varepsilon_t$$

The regressions are repeated in first differences with a single intercept. Autocorrelation-adjusted t-statistics are shown in parentheses.

Cost Measure	Contemporaneous	Future	Contemporaneous (differences)	Future (differences)
Quoted Spread	0.0320 (2.3)	12.2 (8.3)	0.0026 (0.2)	12.3 (1.2)
Effective Spread	0.0326 (0.4)	41.0 (7.3)	−0.0674 (−0.9)	29.8 (2.4)
log(1/Quote Size)	0.0380 (1.1)	10.1 (7.1)	0.0012 (0.0)	10.0 (2.7)
log(1/Trade Size)	0.0243 (0.4)	21.9 (6.8)	−0.0286 (−0.5)	22.2 (3.1)
log(1/# of Quotes)	0.0655 (2.2)	11.6 (6.4)	0.0460 (1.7)	12.6 (2.6)
log(1/# of Trades)	0.0825 (3.3)	5.2 (7.4)	0.0398 (1.8)	5.6 (3.0)
log(1/Volume)	0.0555 (2.6)	4.2 (7.3)	0.0240 (1.3)	4.8 (3.1)

While these results confirm the importance of expected future trading costs in explaining the yield difference between off-the-run and on-the-run notes, we should caution that the measures of contemporaneous liquidity are necessarily noisier than those of future liquidity, since they are averaged over just one day, while future trading costs are calculated as an average over a long time period. Measurement errors in contemporaneous trading costs artificially lower their estimated coefficients which should therefore be interpreted cautiously.

6.3. TIME VS. FUTURE LIQUIDITY

It is possible that there is another effect, unrelated to liquidity, that depends upon the issue cycle, for example, if some bond funds or central banks are restricted to holding on-the-run securities. We know that expected future trading costs decrease over time, so it is conceivable that our results are simply due to the correlation between the future cost measures and the time that a security issue will remain on the run. If that were the case, our regression results would be spurious. We test whether this is true by including a time trend in the regressions which is simply the

Table III. Regression of yield difference on time trend and future trading cost measures

This table shows the results of autocorrelation-adjusted panel regressions of the yield difference (YD_t) on a time trend, (i.e., the time in years since the issue of the on-the-run note), and the (orthogonalized) future trading cost difference for each of the seven cost measures. Fixed-effects dummies are included to control for cross-sectional differences. The regression is run over the first month from the issue of the on-the-run security. Autocorrelation-adjusted t-statistics are shown in parentheses. The regression equation is as follows:

$$YD_t = \sum_{i=1}^{55} \alpha_i I_{it} + \beta\tau_t + \gamma\left(\overline{C}_{off,t} - \overline{C}_{on,t}\right)^{orth} + \varepsilon_t.$$

Cost Measure	Time trend (Fractions of a year from issue)	Future trading cost
Quoted Spread	−7.3 (−7.3)	22.2 (4.3)
Effective Spread	−6.6 (−6.5)	40.4 (3.2)
log(1/Quote Size)	−6.6 (−6.8)	10.5 (2.1)
log(1/Trade Size)	−6.5 (−6.7)	12.8 (1.7)
log(1/Number of Quotes)	−6.6 (−6.7)	0.1 (0.0)
log(1/Number of Trades)	−7.2 (−7.7)	8.8 (3.5)
log(1/Volume)	−7.0 (−7.4)	6.4 (3.0)

time since on-the-run security was issued.[22] We orthogonalize the future trading cost measures against the time trend and the fixed-effect dummies to obtain the following regression model:

$$YD_t = \sum_{i=1}^{55} \alpha_i I_{it} + \beta\tau_t + \gamma\left(\overline{C}_{off,t} - \overline{C}_{on,t}\right)^{orth} + \varepsilon_t, \tag{9}$$

where τ_t denotes the time since the issue of the on-the-run security (measured as a fraction of a year) at each day t. The coefficient β captures the effect of time on the yield difference whether or not this effect is due to changes in expected future liquidity. The coefficient γ captures any remaining effect of liquidity beyond that already captured in the time trend. The regression results are shown in Table III.

The regression coefficients for the time trend are all negative and very significant as a result of the downward slope in the yield difference. However, almost all of the orthogonalized cost measures are also statistically significant. This indicates that these future cost measures are not simply proxying for an unrelated time effect.

22 Sarig and Warga (1989), for example, use a time trend as one proxy for liquidity.

However, trade size is only weakly significant, and the number of quotes is not at all significant beyond that which is already captured in the time trend.[23]

Since the trading cost measures are related to the yield difference even beyond the simple time measure, and since the amount of time that a security remains on the run is an important part of the remaining liquidity, we no longer include a term to separately capture the time elapsed since a security was issued.

6.4. LIQUIDITY AND REPO SPECIALNESS

In this section, we discuss the effect of liquidity on prices when controlling for specialness in the repo market. While the results in the previous subsection include controls for the time since the issuance of the on-the-run security, since specialness in the repo market is particularly related to the on/off cycle, we address it explicitly.

In the repo market, Treasury securities are used as collateral to borrow money. With most Treasuries, particularly off-the-run securities, money is borrowed at the "general collateral" rate. A security is said to be "on special" if its repo rate is below the general collateral repo rate, and thus can be used as collateral to borrow money at a rate below the prevailing interest rate. Put another way, a security which is on special is one that has scarcity value and the owner can earn an extra return beyond its yield by lending out the security. The degree of specialness is the extra return that can be earned by lending the security. Using a model based on the absence of arbitrage, Duffie (1996) analyzes the effect of specialness on prices and shows that such a security should have a higher price than similar securities that are not on special.[24]

Moreover, Keane (1996) shows that specialness is related to the on/off cycle; it is primarily on-the-run Treasuries that are on special. In a study of 30-year Treasury bonds, Krishnamurthy finds that the profits from an on-the-run/off-the-run arbitrage do not survive the extra cost of specialness in borrowing the on-the-run security. However, Jordan and Jordan (1997) find that the yield difference between on-the-run and off-the-run securities exceeds the specialness of the on-the-run.

An important question about the roles of specialness and liquidity that remains unanswered is whether they are separate effects. While liquidity is the ability to easily trade a security, specialness may or may not be directly related to liquidity. On the one hand, a security may trade on special simply because it is more liquid (as in Duffie (1996)). However, specialness could also be a reflection of the scarcity value of the security, for example, it may be related to the supply of the security, or the security may be subject to a short squeeze (see Fleming (2000, 2002)).

The approach we take in this section is to explicitly account for the cost of carry in the repo market. A security that is on special has a larger cost of carry than a nonspecial security. An equivalent way to think about this is that the security can

[23] When we include the time trend in regressions on contemporaneous and future trading costs, as in Table II, we obtain results that are very similar to those in Tables II and III.

[24] Also see the more recent model of Cherian, Jacquier and Jarrow (2004).

be lent out, and the specialness is the extra return earned on the investment. In this section, we control for specialness when measuring the yield difference between the off-the-run and on-the-run securities, YD_t, by adjusting for the extra return earned by the owner of the on-the-run security due to specialness, and then we look for a remaining liquidity effect.

The repo data we use are the GovPX repo indices, which are daily trade-weighted averages of overnight repo rates. The GovPX data includes repo indices for each on-the-run security as well as for general collateral. The GovPX indices begin in November 1995, so our analysis necessarily excludes the early part of our main data set. While off-the-run securities could also be on special, it is an infrequent occurrence, and the GovPX data did not cover specialness for off-the-run securities until very late in our time series. Therefore we assume no specialness in off-the-run securities.

Analogous to the argument made throughout this paper, the specialness adjustment of concern is not the current specialness, but the average specialness over the lifetime of the security. At any time t, the return that can be earned by the holder of a note is its yield plus the average of its future lifetime specialness.

We define the specialness at date t of an on-the-run security as $sp_t = R_{g,t} - R_t\,(\geq 0)$, where $R_{g,t}$ is the general collateral repo rate, and R_t is the security specific repo rate for the on-the-run security at date t. A security is on special if $sp_t > 0$.

Also analogous to the construction of the liquidity measures, we implement the measure of future specialness using the observed specialness averaged from time t onwards. At each date t, we calculate the average future specialness of the on-the-run security as $\overline{sp_t} = \frac{1}{T-t}\sum_{\tau=t}^{T} sp_\tau$, where T is the maturity date of the note.[25] (Although recall that we assume $sp_\tau = 0$ from the date the security goes off the run until the maturity date T.) Since this average future specialness is added to the yield of the on-the-run note, the specialness adjusted yield difference is defined as $YD_t^{sp} = YD_t - \overline{sp_t}$.

Over the time period for which we have repo date, on-the-run securities exhibit specialness, averaging 28 basis points. However, at any date t the more important measure for our purpose is the average future specialness $\overline{sp_t}$. For on-the-run notes in our sample, $\overline{sp_t}$ average 0.78 basis points. This compares to an average yield difference between the on-the-run and off-the-run notes of 1.41 basis points, resulting in a specialness-adjusted yield difference YD_t^{sp} averaging 0.62 basis points.

More important than the averages, if specialness is a reflection of the extra liquidity of the on-the-run security, then after the specialness adjustment to the yields there should no longer be a relation between future liquidity and YD_t^{sp}. However, if specialness is due to scarcity unrelated to liquidity, the relation should remain.

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[25] Following a similar argument, Jordan and Jordan (1997) also sum up future specialness. The role of future specialness is central to Buraschi and Menini (2002).

Table IV. Regression of yield difference on future trading cost measures adjusted for repo specialness

Panel A of this table reports the results of the basic regressions (as in Table I) both in levels and in first differences limited to data for which repo data is available (beginning November 1995). Panel B reports results when the left hand side variable is adjusted for repo specialness. The specialness adjustment adds remaining average lifetime specialness to the yield of the on-the-run security. The regressions are autocorrelation-adjusted panel regressions of the yield difference (YD_t or YD_t^{sp}) on the difference between the future cost measures for off-the-run and on-the-run notes (run separately for each of the seven cost measures). Fixed-effects dummies are included for each pair of securities in order to isolate cross-sectional differences other than liquidity. The regression equation is

$$YD_t^{(sp)} = \sum_{i=1}^{38} \alpha_i I_{it} + \beta \left(\overline{C}_{off,t} - \overline{C}_{on,t}\right) + \varepsilon_t .$$

Partial R^2 for the panel regressions in levels are shown in the last column.

Cost measure	Panel regression	Partial R^2	Panel regression (differences)
	Panel A: Without adjustment for specialness		
Quoted Spread	19.9 (7.9)	6.21%	15.7 (2.3)
Effective Spread	53.7 (6.8)	5.88%	31.8 (1.8)
log(1/Quote Size)	13.8 (6.2)	5.81%	13.3 (2.3)
log(1/Trade Size)	31.2 (6.0)	5.87%	24.3 (2.2)
log(1/# of Quotes)	15.6 (5.2)	4.19%	16.4 (2.1)
log(1/# of Trades)	7.1 (6.5)	4.82%	7.1 (2.5)
log(1/Volume)	6.0 (6.5)	5.21%	6.0 (2.5)
	Panel B: With adjustment for specialness		
Quoted Spread	14.8 (4.5)	3.54%	18.2 (2.2)
Effective Spread	38.8 (4.0)	3.08%	50.0 (2.3)
log(1/Quote Size)	10.4 (3.7)	1.96%	19.1 (2.7)
log(1/Trade Size)	23.4 (3.7)	1.79%	21.4 (1.6)
log(1/# of Quotes)	10.5 (2.7)	0.88%	20.1 (2.1)
log(1/# of Trades)	5.0 (3.7)	1.98%	7.8 (2.2)
log(1/Volume)	4.4 (3.8)	2.02%	6.4 (2.2)

In Panel B of Table IV, we report results for the panel regression of the specialness-adjusted yield difference on the seven measures of future liquidity. Since the repo data only begins in November 1995, to facilitate comparison, Panel A reports the regression results without the specialness adjustment (i.e., the regressions from Table I) for the data set beginning in November 1995.

When considering the regressions in levels, we find that even after adjusting for repo specialness the yield difference between off-the-run and on-the-run notes is related to each of the seven measures of future liquidity. The coefficients (and t-statistics) are somewhat reduced relative to those in the unadjusted regressions, but the relation is still statistically very significant. When the regressions are run in differences, for some specifications, the coefficients are even increased relative to the unadjusted case.

In the above analysis, specialness is subtracted from YD_t to explicitly account for the extra return that the holder of the on-the-run security can earn by lending it. An alternative empirical specification (not reported in the Table) is to include the average future specialness, $\overline{sp_t}$, as an independent variable in the regressions. Under this alternative specification, we find that the difference in future liquidity (regardless of which trading cost measure is used) subsumes the difference in future specialness: when regressing the yield difference YD_t on these variables, the coefficient on future specialness is statistically indistinguishable from zero.

While this result underscores the importance of liquidity relative to specialness, one should keep in mind that it may also be related to investors' ability to predict future liquidity and future specialness. If future liquidity is predictable (because the on/off cycle is predictable) but future specialness is not, then the current yield difference will reflect future liquidity but not future specialness. (Moreover, the explanatory power of specialness may be reduced because of the way that the GovPX indices are constructed. As trade-weighted daily averages, the general collateral and security-specific indices will, in general, be based on trades at different times of day. As such, specialness, which we measure as the difference between two repo rate indices will be measured with error. This results in a downward bias in the coefficient on future specialness.)

In summary, these results suggest that the effect studied in this paper - the relation between Treasury prices and future liquidity is not the same as the phenomenon of specialness in the repo market. The difference in returns between the off-the-run note and the on-the-run note, even after allowing for the extra return due to specialness in the repo market, is related to future liquidity.

6.5. COMPARISON OF LIQUIDITY MEASURES

One of the goals of this paper is to examine the relative importance of the different liquidity measures as determinants of the yield difference. If certain aspects – or certain measures – of illiquidity are more detrimental to investors than others, then investors will require a higher yield on securities that have these characteristics.

The main difficulty in making this comparison is that our trading cost measures are correlated with each other. In order to examine the relative importance of each, we run the regression with pairwise combinations of cost measures. For each pair of cost measures, the difference in future costs (between the off-the-run and the on-the-run securities) under the second measure is orthogonalized relative to the difference in costs under the first measure and relative to the fixed-effects dummies. The regression model is

$$YD_t = \sum_{i=1}^{55} \alpha_i I_{it} + \beta \left(\overline{C}^j_{off,t} - \overline{C}^j_{on,t} \right) + \gamma \left(\overline{C}^k_{off,t} - \overline{C}^k_{on,t} \right)^{orth} + \varepsilon_t \qquad (10)$$

where $\overline{C}^j$ and $\overline{C}^k$ refer to different measures of average future trading costs.

Orthogonalizing the two regressors allows us to measure the incremental explanatory power of measure k beyond measure j. Given the results in Section 6.1, the coefficient of the first measure j will certainly be significantly positive. The question though, is whether the orthogonalized measure k adds explanatory power or if it is subsumed by measure j. Since we have seven expected cost measures and we examine each permutation of pairs there are a total of 42 regressions. The regression results are shown in Panels A and B of Table V and are summarized in Panel C of Table V.

In Panel A the measures listed along the vertical dimension are the nonorthogonalized (first) measures of trading cost, and the orthogonalized (second) measures appear along the horizontal dimension of the table. For each pair of expected cost measures, the regression coefficient and t-statistic of the nonorthogonalized measure is shown first, followed by the coefficient and t-statistic of the orthogonalized measure one line below. Coefficients of orthogonalized measures that are statistically significant (at the one-tailed 5% level) are highlighted in the table with asterisks. Panel B repeats the analysis with differenced regressions.

When examining the regression results in Panel A, certain patterns emerge. The measure that appears most robust in adding explanatory power is the average quoted spread. The quoted spread adds explanatory power relative to each of the other measures, and each of the other measures is subsumed by the quoted spread (i.e., they do not add statistically significant explanatory power when orthogonalized relative to the quoted spread). The effective spread, which is the bid-ask spread immediately before a trade, adds explanatory power relative to some other measures (although not relative to the quoted spread). The effective spread also subsumes most, but not all, other liquidity measures. So although both the quoted and the effective bid-ask spreads are measures of liquidity that are significantly related to yields, the quoted spread appears stronger as it adds explanatory power relative to the effective spread, while the reverse is not true.

Depth measures – average quote size and average trade size – only add explanatory power relative to the weakest of the other measures, and they do not subsume many other measures.

The measures of market activity are the number of quotes per day, the number of trades per day, and volume.[26] The number of quotes per day is the weakest of

[26] One should be cautious in comparing these market activity measures of liquidity to other measures since these may be weakened by a decline in GovPX market share over our sample period.

Table V. Regression of yield differences on pairs of future trading cost measures

This table reports the results of 42 regressions of the yield difference (YD_t) on all permutations of pairs of future trading cost differences, each with one cost measure orthogonalized relative to the other. In the regressions in levels, fixed-effects dummies are included to control for cross-sectional differences. Autocorrelation-adjusted t-statistics are shown in parentheses. The regressions are run over the first month from the issue date of the on-the-run security. The regression equation is as follows:

$$YD_t = \sum_{i=1}^{55} \alpha_i I_{it} + \beta \left(\overline{C}^j_{off,t} - \overline{C}^j_{on,t} \right) + \gamma \left(\overline{C}^k_{off,t} - \overline{C}^k_{on,t} \right)^{orth} + \varepsilon_t ,$$

where j and k refer to the nonorthogonalized and orthogonalized trading costs, respectively. The nonorthogonalized trading cost measures are shown along the vertical dimension of the table and the orthogonalized measures are shown along the horizontal dimension. The first set of numbers for each trading cost pair refers to the nonorthogonalized cost measure and the second set of number refers to the orthogonalized measure. Asterisks denote coefficients of the orthogonalized cost measures that add explanatory power at the one-tailed 5% significance level.

Panel A. Fixed-effect regressions in levels

	Quoted spread (orth)	Effective spread (orth)	log of 1/Qt Size (orth)	log of 1/Trd Size (orth)	log of 1/# Qts (orth)	log of 1/# Trds (orth)	log of 1/Vol (orth)
Quoted		22.1 (10.8)	21.9 (10.6)	20.6 (10.1)	22.3 (10.8)	21.5 (10.1)	21.3 (10.1)
Spread		−16.6 (−0.9)	−14.3 (−2.1)	−9.6 (−0.9)	−34.9 (−3.4)	−3.7 (−1.0)	−3.6 (−1.2)
Effective	69.1 (14.6)		66.6 (14.1)	65.7 (14.1)	66.5 (14.5)	67.0 (14.2)	66.9 (14.2)
Spread	24.6 (3.9)*		4.0 (0.9)	8.1 (0.9)	0.1 (0.0)	4.1 (1.8)*	3.2 (1.6)
log of	17.3 (9.7)	16.0 (8.6)		15.5 (8.8)	15.0 (8.6)	16.6 (9.5)	16.2 (9.1)
1/Qt Size	34.3 (4.4)*	35.3 (2.2)*		10.1 (0.8)	−48.0 (−3.6)	19.3 (3.3)*	15.7 (3.0)*
log of	46.6 (13.2)	45.8 (12.8)	44.5 (12.3)		43.4 (11.58)	44.8 (12.8)	44.8 (12.8)
1/Trd Size	20.4 (4.1)*	36.0 (2.8)*	10.3 (1.9)*		3.8 (0.6)	8.6 (3.5)*	8.4 (3.5)*
log of	20.5 (8.9)	18.2 (7.4)	17.6 (7.8)	18.3 (7.7)		19.6 (9.4)	18.7 (8.7)
1/# Qts	48.0 (5.2)*	48.2 (2.9)*	48.2 (4.5)*	28.8 (2.4)*		37.7 (6.8)*	32.9 (6.7)*
log of	7.9 (8.7)	7.4 (8.0)	7.7 (9.0)	7.4 (8.7)	8.0 (10.2)		7.5 (8.8)
1/# Trds	26.1 (2.9)*	21.7 (1.3)	−23.8 (−2.1)	−2.2 (−0.2)	−82.5 (−5.8)		−6.5 (−0.6)
log of	6.9 (9.2)	6.5 (8.4)	6.6 (9.1)	6.6 (9.2)	6.6 (9.8)	6.6 (9.3)	
1/Vol	27.6 (3.1)*	23.1 (1.4)	−23.8 (−1.9)	−8.8 (−0.7)	−86.4 (−5.6)	15.0 (1.2)	

our seven liquidity measures. It neither adds explanatory power relative to any of the other measures, nor does it subsume any other liquidity measure. In contrast, the trade-based measures of market activity – the number of trades and volume – add explanatory power relative to most of the other measures and also subsume most of them.

The results for differenced regressions in Table V, Panel B are largely similar.

Panel C is a concise summary of the results in Panels A and B. For each of the liquidity measures, we count the number of times it adds statistically significant explanatory power (at the one-tailed 5% level) relative to the other six measures. We also count the number of times it subsumes the other measures (i.e., the other measures do not add statistically significant incremental explanatory power). From

Table V. Panel B. Regression in first differences with a single intercept

	Quoted spread (orth)	Effective spread (orth)	log of 1/Qt Size (orth)	log of 1/Trd Size (orth)	log of 1/# Qts (orth)	log of 1/# Trds (orth)	log of 1/Vol (orth)
Quoted		27.7 (2.7)	48.1 (3.1)	33.5 (3.1)	30.6 (1.9)	47.5 (3.2)	50.7 (3.5)
Spread		21.4 (0.9)	29.4 (1.8)*	23.2 (1.6)	6.4 (0.3)	16.0 (1.9)*	15.4 (2.2)*
Effective	66.5 (2.8)		104.1 (3.0)	59.7 (2.8)	75.6 (2.0)	108.7 (3.3)	114.8 (3.5)
Spread	21.0 (1.7)*		33.8 (2.2)*	24.8 (1.8)*	21.3 (1.0)	18.3 (2.4)*	16.9 (2.7)*
log of	45.7 (3.0)	42.3 (2.8)		40.8 (2.7)	42.7 (2.4)	51.9 (3.2)	52.9 (3.3)
1/Qt Size	19.3 (1.7)*	30.6 (1.5)		18.0 (1.2)	6.0 (0.3)	15.6 (1.8)*	15.3 (2.0)*
log of	56.0 (3.1)	41.7 (2.7)	70.8 (2.9)		53.2 (2.0)	77.0 (3.2)	79.3 (3.2)
1/Trd Size	24.3 (2.3)*	37.4 (1.9)*	33.6 (2.1)*		23.9 (1.1)	18.7 (2.5)*	19.6 (2.5)*
log of	35.0 (1.7)	34.5 (1.7)	53.7 (2.3)	36.5 (1.7)		53.0 (2.4)	54.4 (2.5)
1/# Qts	25.7 (2.1)*	36.8 (1.8)*	38.3 (2.2)*	25.0 (1.7)*		22.3 (2.6)*	20.8 (2.9)*
log of	22.4 (3.1)	22.0 (3.1)	25.7 (3.2)	22.2 (3.1)	21.0 (2.5)		23.1 (3.2)
1/# Trds	15.0 (1.2)	26.8 (1.3)	21.3 (1.1)	17.7 (1.2)	−3.7 (−0.2)		17.8 (1.2)
log of	20.3 (3.4)	19.9 (3.3)	22.2 (3.3)	19.5 (3.1)	18.3 (2.6)	19.6 (3.2)	
1/Vol	14.0 (1.2)	25.4 (1.3)	17.4 (0.9)	−0.4 (−0.0)	−8.2 (−0.3)	2.2 (0.1)	

Table V. Panel C. Scoring of trading cost measures

This panel summarizes the information in Panels A and B of Table IV. In the previous panels each of the seven trading cost measures k is orthogonalized relative to each of the other cost measures j. If the orthogonalized measure k is statistically significant (at the one-tailed 5% level) in a regression with measure j, we say that measure k adds explanatory power relative to j. If not, we say that measure j subsumes measure k. For each measure of liquidity, we count the number of times (out of a possible six) it adds explanatory power relative to the other liquidity measures. We also count the number of times it subsumes other measures (out of a possible six times). The total score is the sum of these counts.

Cost Measure	Adds explanatory power	Subsumes other measures	Adds Explanatory power (differences)	Subsumes other Measures (differences)	Total
Quoted spread	6	6	4	3	19
Effective spread	3	4	2	1	10
log(1/Quote Size)	2	2	4	3	11
log(1/Trade Size)	1	1	2	1	5
log(1/# of Quotes)	0	0	0	0	0
log(1/# of Trades)	4	5	5	6	20
log(1/Volume)	3	5	5	6	19

this summary we see again that the quoted spread, the number of trades and volume are most important in explaining the yield difference.

It is noteworthy that when considering the effect of bid-ask spreads on the yield difference, quotes are more important than trades. This may reflect the need for immediacy – the ability to trade a position at any time at the quoted spread without waiting for the spread to narrow. In contrast, as measures of market activity, the number of trades and volume have a greater effect on prices than the number of quotes. This may capture the time required to find a counterparty to complete a trade at a fair price when immediacy is not needed.

6.6. TIME-VARYING VALUE OF LIQUIDITY

Until this point we have shown that future trading costs are impounded into security prices, but our analysis assumes that the effect of illiquidity on prices remains constant over time. However, it is possible that the market's discount per unit of illiquidity varies - at times the market values liquidity a great deal and times it values liquidity less. In the context of our model, this would be if the probability of a liquidity shock to the marginal investor varies depending on the economic state of the world.

In this section, we test for a time-varying value of liquidity. We implement this empirically with a number of proxies to capture the market's preference for liquidity, and interacting these proxies with the difference in future trading costs between off-the-run and on-the-run notes.

The proxies we use are the commercial paper (CP) spread (similar to that used by Krishnamurthy (2002)), the volatility of short-term and long-term interest rates (as suggested in Kamara (1994)), and equity market volatility. The commercial paper spread is measured each day as the yield difference between illiquid six-month commercial paper and six-month Treasury bills. The two interest rate volatility measures are the annualized standard deviations of yield on three-month Treasury bills and 30-year Treasury bonds, respectively, measured over the previous ten days. Equity market volatility is the annualized standard deviation of returns on the S&P 500 also measured over the previous ten days.

We use the following regression to test for this effect:

$$YD_t = \sum_{i=1}^{55} \alpha_i I_{it} + \beta \left(\overline{C}_{off,t} - \overline{C}_{on,t}\right) + \gamma V_t \left(\overline{C}_{off,t} - \overline{C}_{on,t}\right) + \varepsilon_t, \qquad (11)$$

where V_t is the value of the proxy (measured in percentage points) for the time-varying value of a unit of liquidity, β captures the effect of future illiquidity on prices that is not time varying, and γ captures the interaction between future trading costs and the proxy. A positive estimate of γ would suggest that the market values each unit of future liquidity more when V_t is higher. This regression is run for each of the seven trading cost measures and each of the four proxies.

The results are presented in Table VI. When the commercial paper spread is used as a proxy for the markets preference for liquidity, we find that for all measures of future trading costs other than quoted spread, the coefficient of the interaction term is positive and significant. Similarly, three-month Treasury yield volatility and, to a slightly lesser extent, 30-year bond yield volatility are statistically significant when interacted with most measures of future trading costs.

Table VI. Regression of yield difference on future trading cost measures interacted with CP spread, yield volatility, and equity volatility

This table shows the results of autocorrelation-adjusted panel regressions of the yield difference (YD_t) on the future trading cost difference for each of the seven cost measures, and the future trading costs interacted with a proxy for potentially time-varying market valuation of liquidity (V_t). We use four such proxies (resulting in twenty eight separate regressions) which are (i) the difference between the yield on six-month commercial paper and the yield on six-month Treasury bills, (ii) the three-month Treasury bill yield volatility, (iii) the thirty-year Treasury bond yield volatility, and (iv) the S&P 500 return volatility. All proxies are measured in percentage points, and the volatilities are (annualized) standard deviations measured over the previous ten days. Fixed-effects dummies are included to control for cross-sectional differences. The regression is run over the first month from the issue date of the on-the-run security. The regression equation is as follows:

$$YD_t = \sum_{i=1}^{55} \alpha_i I_{it} + \beta\left(\overline{C}_{off,t} - \overline{C}_{on,t}\right) + \gamma V_t\left(\overline{C}_{off,t} - \overline{C}_{on,t}\right) + \varepsilon_t.$$

Autocorrelation-adjusted t-statistics are shown in parentheses.

Cost Measure		Difference in future trading costs interacted with: CP spread	Yield volatility (3-month T-bill)	Yield volatility (30-year T-bond)	S&P return volatility
Quoted Spread	β	15.3 (10.0)	14.3 (9.0)	14.3 (9.2)	16.2 (8.1)
	γ	1.9 (1.4)	1.43 (2.7)	1.44 (2.9)	0.050 (1.4)
Effective Spread	β	38.3 (12.3)	36.9 (10.1)	40.3 (10.7)	41.9 (7.0)
	γ	7.7 (2.2)	3.57 (2.8)	1.63 (1.5)	0.229 (2.1)
log(1/Quote Size)	β	9.6 (7.0)	10.3 (7.5)	11.1 (8.3)	12.0 (7.0)
	γ	6.0 (2.5)	2.28 (2.8)	1.14 (1.8)	0.119 (1.8)
log(1/Trade Size)	β	25.0 (10.0)	27.9 (9.8)	27.3 (9.9)	27.3 (6.8)
	γ	8.0 (2.9)	−0.29 (−0.3)	0.89 (1.0)	0.175 (2.0)
log(1/# of Quotes)	β	13.5 (7.5)	13.6 (6.8)	13.6 (7.0)	14.8 (6.7)
	γ	2.6 (2.1)	1.15 (2.5)	1.06 (2.8)	0.101 (2.7)
log(1/# of Trades)	β	4.8 (6.5)	5.0 (6.7)	5.3 (7.0)	6.2 (7.4)
	γ	2.6 (2.3)	1.33 (3.2)	1.08 (2.9)	0.059 (1.9)
log(1/Volume)	β	4.4 (7.6)	4.5 (8.1)	4.7 (8.4)	5.2 (7.4)
	γ	1.7 (2.3)	0.87 (2.9)	0.66 (2.5)	0.058 (2.5)

This suggests that the value of liquidity does indeed vary over time, and that the commercial paper spread, as well as both short-term and long-term Treasury yield volatilities, are valid proxies for the market price of liquidity. Interestingly, equity market volatility is also statistically significant when interacted with future trading costs, suggesting that the time-varying value of liquidity in the Treasury market is related to uncertainty in the equity market.

The economic significance of the coefficient estimates of the interaction term can be interpreted as the increase in the value of liquidity per percentage point increase in the proxy. For example, when the effective spread is used as the measure of trading costs, if the CP spread were to rise from 0% to 1%, the effect of future trading costs on yields would rise by 7.7 from 38.3 to 46.0. In general, for a given proxy and a given measure of future trading costs, the economic significance of the interaction term can be measured as the ratio of the effect of a one percentage point change in the proxy to the average effect of future trading costs on yields; i.e., $\widehat{\gamma}/\left(\widehat{\beta}+\widehat{\gamma}\overline{V}\right)$, where $\widehat{\beta}$ and $\widehat{\gamma}$ are the coefficient estimates and $\overline{V}$ is the average value of the proxy over our sample.

For the CP spread this ratio averages 0.28 over the seven liquidity measures. Thus, the market price of future liquidity rises by about 28% per percentage point rise in the commercial paper spread. For short-term and long-term Treasury yield volatilities, the ratio averages 0.13 and 0.10, respectively, with a corresponding increase in the value of future liquidity for each percentage point rise in the annualized standard deviation of Treasury yields. The ratio for equity market volatility averages only 0.007, but the variation in the volatility of equity returns is more than an order of magnitude greater than that in the volatility of interest rates.

7. Conclusion

This paper examines the effect of liquidity on on-the-run and off-the-run U.S. Treasury notes. Unlike the previous empirical literature, but in line with the theoretical literature, we focus on future liquidity rather than just current liquidity. We are able to do so because liquidity varies predictably over the on/off cycle in the Treasury market. Our paper also differs from the previous literature in the sense that we look at differences in liquidity and yields of securities in time-series regressions. This allows us to disregard any fixed cross-sectional differences between securities. We use a number of different liquidity proxies based on quotes and trades

We find that the price premium for liquid securities does indeed depend primarily on future liquidity. This result holds even when we adjust for specialness in the repo market. When comparing different measures of liquidity, we find that each measure significantly explains the yield difference between off-the-run and on-the-run notes. When orthogonalized relative to each other, the quoted spread and measures of market trading activity, (i.e., the number of trades and volume) add the most incremental explanatory power relative to other measures. Depth measures (i.e. average quote and trade sizes) and especially the number of daily quotes add little incremental explanatory power.

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