An Index of Treasury Market Liquidity: 1991-2017 *

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Abstract

Order book and transactions data from the U.S. Treasury securities market are used to calculate daily measures of bid-ask spreads, depth, and price impact for a twenty-six-year sample period (1991-2017). From these measures, a daily index of Treasury market liquidity is constructed, reflecting the fact that the varying measures capture different aspects of market liquidity. The liquidity index is then correlated with various metrics of funding liquidity and volatility. The liquidity index points to poor liquidity during the 2007-09 financial crisis and around the near-failure of Long-Term Capital Management, and suggests that current liquidity is good by historical standards. Market liquidity tends to be strongly correlated with funding liquidity at times of market stress, but otherwise exhibits little correlation.

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1 Introduction

U.S. Treasury securities occupy a central role in global financial markets. As widely recognized safe and liquid benchmark assets, Treasuries are used as reserve assets by central banks, as a store of value by investors, as a source of funding through repurchase agreements, as collateral in a variety of asset markets, and as a hedge against market volatility (International Monetary Fund (2012), Gorton and Ordoñez (2011), Adrian, Crump, and Vogt (2016)). This safety and liquidity is priced in the form of extraordinarily low yields, as investors willingly pay a premium to hold securities with money-like features (Krishnamurthy and Vissing-Jorgensen (2012)). Liquidity is a key attribute that is inextricably linked to the pricing and widespread use of U.S. Treasuries.

In recent years, Treasury market liquidity has taken on special interest because of its behavior during the 2007-09 financial crisis, because of post-crisis regulatory changes, and because of the increasing role of high-frequency trading firms (HFTs) in the market. Engle, Fleming, Ghysels, and Nguyen (2012) document the liquidity disruptions in the most actively traded Treasury securities during the crisis and Musto, Nini, and Schwarz (2016) explore the unusual pricing discrepancies that arose among less actively traded securities. Adrian, Fleming, Shachar, and Vogt (2017) describe the post-crisis regulatory changes and how they may have affected liquidity in dealer-intermediated markets such as the Treasury market. The Joint Staff Report (2015) examines the October 2014 flash rally in the Treasury market and shows that HFTs now account for the majority of activity in the so-called interdealer market.

Despite its importance, no studies have used order book and transactions data to assess Treasury market liquidity over an extended period. Some studies have examined liquidity using order book data over relatively short time spans (e.g., Fleming (2003), Engle, Fleming, Ghysels, and Nguyen (2012), and Adrian, Fleming, Shachar, and Vogt (2017)). Other studies have taken a longer-term focus relying on liquidity proxies, such as the yields on Refcorp bonds relative to Treasuries (Longstaff (2004)) or the dispersion of Treasury security yields around a smooth yield curve (Hu, Pan, and Wang (2013)). Still other studies, such as Goyenko and Ukhov (2009), Goyenko, Subrahmanyam, and Ukhov (2011), and Goyenko and Sarkissian (2014) have used bid-ask spread data from the Center for Research in Security Prices (CRSP). As explained in Duffee (1996), CRSP bid-ask spreads have at times been based on a maturity-dependent "spread curve" that does not change from day to day (that is, the spreads are indicative and seemingly do not change with market conditions), calling into question the information content of such spreads.

In this paper, we assess Treasury market liquidity over a 26-year sample period using order book and transactions data from the interdealer market. In particular, we look at GovPX data from the voice interdealer brokers for the 1991 to 2000 period and data from the BrokerTec electronic trading platform for the 2001 to 2017 period. The measures we focus on are bid-ask spreads, depth, and price impact, although we also examine trading volume, trade frequency, trade size, and volatility.

Interestingly, we find little correlation between our bid-ask spread series and those of CRSP. Moreover, the CRSP series remain unchanged for years at a time, including through the depths of the 2007-09 financial crisis. Further investigation suggests that CRSP relies on indicative end-of-day quotations, whereas our bid-ask spreads are based on actual order book data. The evidence suggests that the CRSP bid-ask spread series have little informational value over our sample period.

The paper also develops a daily index of Treasury market liquidity. We do this by combining our bid-ask spread, depth, and price impact measures, reflecting the fact that the measures capture different aspects of market liquidity. The index, and the underlying measures, point to poor liquidity during the financial crisis and around the near-failure of Long-Term Capital Management (LTCM), and suggests that current liquidity is quite good by historical standards.

Lastly, the paper explores how our liquidity index correlates with measures of funding liquidity and volatility. We show that market liquidity and funding liquidity are strongly correlated during times of crises or market disruption, including the financial market turmoil in fall 1998 around the near-failure of LTCM, the 2007-09 financial crisis, and, to some extent, around the September 11, 2001 attacks and the 2013 taper tantrum. This finding supports theories that link market liquidity to funding liquidity (e.g., Brunnermeier and Pedersen (2009)) and complements the finding of Adrian, Etula, and Muir (2014) that dealer balance sheet leverage is priced in the cross-section of stocks and bonds. That said, market liquidity and funding liquidity exhibit little correlation during more normal times, suggesting that funding constraints in the Treasury market only impact market liquidity under unusual circumstances.

The paper proceeds as follows. Section 2 describes the structure of the secondary Treasury market, focusing on the interdealer market in which dealers trade with one another. Section 3 discusses the order book and transactions data used in the study, and the additional variables used to better understand liquidity. Section 4 presents our main empirical findings, including time series measures of market liquidity, a comparison of GovPX/BrokerTec bid-ask spreads to CRSP bid-ask spreads, our Treasury liquidity index, and the relationship of market liquidity to our funding liquidity and volatility variables. Section 5 concludes.

2 Treasury Market

The secondary market for U.S. Treasury securities is a multiple dealer, over-the-counter market. Traditionally, the predominant market makers were the primary government securities dealers, those dealers with a trading relationship with the Federal Reserve Bank of New York. The dealers trade with the Fed, their customers, and one another. The core of the market is the interdealer broker (IDB) market, which accounts for nearly all interdealer trading. Trading in the IDB market takes place 22-23 hours per day during the week, although the vast majority of trading occurs during New York hours, roughly 07:00 to 17:30 Eastern time (Fleming (1997)).

Until 1999, nearly all trading in the IDB market occurred over the phone via voice-assisted brokers. Voice-assisted brokers provide dealers with proprietary electronic screens that post the best bid and offer prices called in by the dealers, along with the associated quantities. Quotes are binding until and unless withdrawn. Dealers execute trades by calling the brokers, who post the resulting trade price and size on their screens. The brokers thus match buyers and sellers, while ensuring anonymity, even after a trade. In compensation for their services, brokers charge a fee.

Most previous research on the microstructure of the Treasury market has used data from voice-assisted brokers, as reported by GovPX, Inc.[1] GovPX receives market information from IDBs and re-disseminates the information in real time via the internet and data vendors. Infor-

[1] See, for example, Fleming and Remolona (1999), Brandt and Kavajecz (2004), and Pasquariello and Vega (2007).

mation provided includes the best bid and offer prices, the quantity available at those quotes, and trade prices and volumes. In addition to the real-time data, GovPX sells historical tick data, which provides a record of the real-time data feed for use by researchers and others.

When GovPX started operations in June 1991, five major IDBs provided it with data, but Cantor Fitzgerald did not, so that GovPX covered about two-thirds of the interdealer market. The migration from voice-assisted to fully electronic trading in the IDB market began in March 1999 when Cantor Fitzgerald introduced its eSpeed electronic trading platform.[2] In June 2000, BrokerTec Global LLC, a rival electronic trading platform, began operations.[3] As trading of on-the-run securities migrated to these two electronic platforms, and the number of brokers declined due to mergers, GovPX's data coverage dwindled. By the end of 2004, GovPX was receiving data from only three voice-assisted brokers. After ICAP's purchase of GovPX in January 2005, ICAP's voice brokerage unit was the only brokerage entity reporting through GovPX.

BrokerTec and eSpeed are fully automated electronic trading platforms on which buyers are matched to sellers without human intervention. Both brokers provide electronic screens that display the best bid and offer prices and associated quantities. On BrokerTec, a manual trader can see five price tiers and corresponding total size for each tier on each side of the book, plus individual order sizes for the best 10 bids and offers. For computer-based traders, the complete order book is available. Traders enter limit orders (minimum order size is $1 million par value) or hit/take existing orders electronically, with priority of execution of limit orders based on price and time. As with the voice brokers, the electronic brokers ensure trader anonymity, even after a trade, and charge a small fee for their services.

The BrokerTec platform allows iceberg orders, whereby a trader can choose to show only part of the amount he is willing to trade. As trading takes away the displayed portion of an iceberg order, the next installment of hidden depth equal to the pre-specified display size is shown. This process continues until trading completely exhausts the iceberg order. It is not possible to enter

[2]Cantor spun eSpeed off in a December 1999 public offering. After many ownership changes, eSpeed merged with BGC Partners, an offshoot of the original Cantor Fitzgerald. In 2013, eSpeed was purchased by NASDAQ OMX Group.

[3]BrokerTec had been formed the previous year as a joint venture of seven large fixed income dealers. BrokerTec was acquired in May 2003 by ICAP PLC. ICAP changed its name to NEX Group PLC in December 2016.

iceberg orders with zero displayed quantity; that is, limit orders cannot be completely hidden.

Beside iceberg orders, the electronic brokers have retained a workup feature, similar to the expandable limit order protocol of the voice-assisted brokers, but with some important modifications.[4] On BrokerTec, the most important difference is that the right-of-first-refusal previously given to the original parties to the transaction has been eliminated, giving all market participants immediate access to workups. All trades consummated during a workup are assigned the same aggressive side as the original market order.[5]

In the early days of BrokerTec, platform participants were limited to government securities dealers. However, since 2004, BrokerTec has opened access to non-dealer participants, including hedge funds and HFTs. Table 3.3 (p. 59) in the Joint Staff Report (2015) on the U.S. Treasury market shows that HFTs account for 56% of trading volume in the on-the-run 10-year note, compared to bank-dealers' share of 35%. The remaining 9% is split among non-bank dealers and hedge funds.[6] These statistics show that the interdealer market for U.S. Treasury securities, despite the name, is no longer solely for dealers.

3 Data

3.1 Order Book and Transactions Data

We rely on order book and transactions data from GovPX and BrokerTec to analyze Treasury market liquidity. The GovPX database contains information for when-issued, on-the-run, and off-the-run Treasury bills, notes, and bonds, whereas the BrokerTec database contains information for on-the-run Treasury notes and bonds only. The GovPX database, which starts June 17, 1991, contains information on prices and (since July 1994) depth at the inside tier of the limit order book, as well as trade prices and (until April 2001) volume. In contrast, our BrokerTec database,

[4] Boni and Leach (2004) provide a thorough explanation of this feature in the voice-assisted trading system. The protocol allows a Treasury market trader whose order has been executed to have the right-of-first-refusal to trade additional volume at the same price. As a result, the trader might be able to have his market order fulfilled even though the original quoted depth is not sufficient. That is, the quoted depth is expandable.

[5] For a detailed analysis of workup activity on the BrokerTec platform, see Fleming and Nguyen (2013).

[6] The mentioned statistics are based on trading activity on the BrokerTec platform from April 2-17, 2014.

which starts January 2, 2001, contains a complete record of every order placed on the platform.[7] We generate prices and depth at the inside tier by fully reconstructing the limit order book.

We limit our analysis to the on-the-run 2-, 5-, and 10-year notes. On-the-run securities are the most recently auctioned securities of a given maturity. As mentioned, we only have access to BrokerTec data for the on-the-run notes and bonds, and the 2-, 5-, and 10-year notes are the only coupon-bearing securities that were continuously issued over our sample period.[8]

Because trading activity has migrated in recent years from the voice-assisted brokers to the electronic platforms, the representativeness of the databases changes over time. In particular, GovPX coverage is high early in the sample, but falls sharply in 1999 and 2000. Fleming (2003) thus finds that GovPX coverage of the interdealer market is 57% in 1998, but 52% in 1999, and just 42% in the first quarter of 2000. In contrast, BrokerTec coverage starts modestly in 2001, but has high coverage for recent years. Fleming and Nguyen (2013) compare BrokerTec trading activity with that of eSpeed reported in Luo (2010) and Dungey, Henry, and McKenzie (2013) and find that BrokerTec accounts for 57-60% of electronic interdealer trading in the on-the-run 2-, 5-, and 10-year notes over the January 2005 to May 2008 sample period.

In our analysis, we use GovPX data from June 1991 to December 2000 and BrokerTec data from January 2001 to December 2017. This provides good coverage of the interdealer market for most of our 26-year sample period, but limited coverage for roughly the 1999 to 2004 period, first when GovPX coverage was declining, and then when BrokerTec activity was increasing. The limited coverage for the 1999 to 2004 period would tend to bias our liquidity measures and suggest historically poor liquidity at that time despite the absence of financial crises. It is for this reason that we choose to adjust the liquidity measures over this period.[9]

[7] Indicators of which side initiated a trade are only available from April 8, 2002.

[8] While the Treasury currently also issues 3-, 7-, and 30-year coupon securities, issuance of the 3-year note was suspended between May 2007 and November 2008, issuance of the 7-year note was suspended between April 1993 and February 2009, and issuance of the 30-year bond was suspended between August 2001 and February 2006.

[9] Specifically, we adjust our raw liquidity measures, discussed in the next section, by scaling them to the roughly 57-60% coverage levels of 1998 and 2005. For the 1998 to 2000 sample period, in which we rely on GovPX data, we first regress each of our liquidity measures on the Merrill Lynch Option Volatility Estimate index (MOVE), the Chicago Board Options Exchange Volatility Index (VIX), and the share of weekly interdealer trading accounted for by GovPX for the 2-, 5-, and 10-year notes (overall interdealer trading is reported weekly by the Federal Reserve Bank of New York via its FR 2004 statistical release). We use the trade volume share coefficient from the regression results to scale

Daily trading activity over time is plotted in Figure 1, and daily trading activity summary statistics are reported in Table 1, with statistics for the GovPX sample period in Panel A, the BrokerTec sample period in Panel B, and the full sample period in Panel C. For the full sample period, daily trading volume averages roughly $16-22 billion per note, average number of trades per day ranges from about 630 to 1560, and average trade size range from about $10.1 million to $24.8 million.[10]

Figure 1 and Table 1 further show a significant upward trend in trading activity over the period from 1991 to 2017. For the GovPX sample period, daily trading volume averages about $3-5 billion per note. This average grows to about $22-31 billion in the BrokerTec sample, or about a four- to eight-fold increase, with the greatest increase occurring in the 10-year note. Trade frequency also rapidly expanded in the BrokerTec period: for instance, trading in the 10-year note increased from roughly 570 trades per day to over two thousand trades per day. Meanwhile, the average trade size more than doubled.

3.2 Funding Liquidity and Volatility Measures

The funding liquidity measures we employ are as follows:

1. The Baa spread, calculated as the yield on Moody's Baa corporate bond index less the constant-maturity yield for the 10-year Treasury note, which Krishnamurthy and Vissing-Jorgensen (2012) cite as a funding liquidity indicator (source: Federal Reserve Bank of St.

the measures for 1999 and 2000 to the 1998 level of coverage. A similar approach is followed with the BrokerTec data, in which the measures for 2001 to 2004 are scaled to the 2005 level of coverage. The trading activity measures are not adjusted (because our analysis of those is mostly descriptive) and the liquidity measures are not adjusted outside of the 1999 to 2004 period.

[10] In calculating the number of trades per day and trade size, every order match within a given workup is counted as part of the same trade. This is the most reliable way to calculate trade size using GovPX data because the volume field in the dataset used to uniquely identify trades only changes when a workup is complete (and reflects the full size of the workup). We follow the same trade definition with the BrokerTec data for consistency. However, the workup protocol was only introduced to the BrokerTec platform on April 8, 2002, making it impossible to precisely implement our workup-delineated trade definition from January 2, 2001 to April 5, 2002. Instead, over our early BrokerTec sample, we calculate an alternate trade frequency measure that defines a trade as a single *instance of trading* (a precise timestamp when one aggressive order is matched to one or more passive orders) for the same security. Over the first several quarters when both this measure and the workup-delineated measure are available (April 8, 2002 - December 31, 2003), we calculate the average ratio of the two for each security. For January 2, 2001 - April 5, 2002, the daily trade frequency measure (also used to calculate trade size) becomes the trade instance measure, scaled down by this average ratio.

Louis).

2. The on-the-run/off-the-run spread, which captures the yield investors forego in order to hold the most recently-issued 10-year Treasury note (Krishnamurthy (2002)). The spread is calculated (using parameters from the Nelson-Siegel-Svensson model of Gurkaynak, Sack, and Wright (2007)) as the yield of a hypothetical security with the same cash flows as the on-the-run 10-year note less the actual yield of the note (source: Board of Governors of the Federal Reserve System, BrokerTec, GovPX).

3. The Refcorp spread, calculated as the yield spread between a 10-year Resolution Funding Corporation zero-coupon bond and a 10-year zero-coupon Treasury bond (source: Bloomberg). Refcorp is a government-sponsored enterprise that provided funds to the Resolution Trust Corporation, which was established to finance the bailout of savings and loan associations in the wake of the savings and loan crisis of the 1980s in the United States. Longstaff (2004) argues that since Refcorp bonds and Treasury securities are equally creditworthy, but Refcorp bonds are much less liquid, the Refcorp spread solely reflects the value of the liquidity difference.

4. The spline error, calculated as the average absolute yield curve fitting error from the Nelson-Siegel-Svensson model of Gurkaynak, Sack, and Wright (2007), a measure of dealers' risk bearing capacity (see Hu, Pan, and Wang (2013); source: Board of Governors of the Federal Reserve System).

5. The swap spread, calculated as the average spread between the 2-, 5-, and 10-year interest rate swap rate and the yield on the corresponding on-the-run Treasury note (source: Bloomberg).

6. The TED (Treasury-eurodollar) spread, a measure of financial market stress, calculated as the spread between 3-month LIBOR and the 3-month Treasury bill rate (source: Federal Reserve Bank of St. Louis).

The volatility measures we use are:

1. The Merrill Lynch Option Volatility Estimate index (MOVE), a measure of implied Treasury volatility (source: Haver Analytics),

2. The Chicago Board Options Exchange Volatility Index (VIX), a measure of implied equity volatility (source: Haver Analytics),

3. Realized volatility, calculated as the inverse maturity-weighted average of realized volatility for each of the 2-, 5-, and 10-year notes, calculated for each note as the sum of squared five-minute log differences in the bid-ask midpoint, annualized by multiplying by 252 (sources: BrokerTec, GovPX).

These funding liquidity and volatility measures are summarized in Table 2.

4 Treasury Market Liquidity

4.1 Liquidity Measures

To assess Treasury market liquidity, we calculate bid-ask spreads, depth, and price impact. The bid-ask spread is one of the most direct measures of market liquidity as it directly measures the cost of trade execution (albeit only a single trade of limited size). The bid-ask spread is calculated for each security and day as the average spread between the best bid and the best offer in the limit order book, as reported by GovPX or BrokerTec. In calculating the average, we limit our analysis to New York trading hours (07:00 to 17:00 Eastern time) and weight all ticks (changes in the order book at any of the inside 10 tiers) equally, implicitly giving greater weight to more active times of day.

Average daily bid-ask spreads are plotted in the top panel of Figure 2, and summary statistics are reported in Table 3. Spreads are quite narrow, with full sample averages of 0.8 basis points for the 2-year note, 1.0 basis points for the 5-year note, and 2.0 basis points for the 10-year note. The spreads are relatively wide and variable over the GovPX and early BrokerTec periods and narrow and stable since 2005, except for an increase during the 2007-09 financial crisis.

While the bid-ask spread directly measures transaction costs and hence liquidity, it does not account for the depth of the market and hence how costs might vary for multiple trades or trades larger than the minimum size. Another limitation of the measure is that the minimum tick size is frequently constraining, which may explain the limited variation in the spread after 2005.[11]

The quantity of securities that can be traded at the various bid and offer prices helps account for the depth of the market and complements the bid-ask spread as a measure of market liquidity. Depth is calculated for each security and day as the average quantity sought at the best bid price plus the average quantity offered at the best ask price. The quantities only include shown amounts in the limit order book and hence exclude quantities hidden through iceberg orders as well as latent depth that gets revealed through the workup process. As with the bid-ask spread, we limit our analysis to New York trading hours and weight all ticks equally. Moreover, because of the long time span covered by the study, we inflation-adjust depth to 2017 dollars using the GDP deflator (obtained from Haver Analytics).

Average daily depths are plotted in the second panel in Figure 2, and summary statistics are reported in Table 3.[12] Average depth at the inside tier is far and away greatest for the 2-year note, averaging $494 million for the full sample period, versus $82 million for the 5-year note and $70 million for the 10-year note. Depth is much greater on BrokerTec than it was on GovPX, with the 2-year note showing a ten-fold increase. Moreover, depth shows tremendous variation on BrokerTec, plunging during the 2007-09 financial crisis and again dropping during the 2013 taper tantrum and around the time of the October 2014 flash rally. By contrast, bid-ask spreads show a more muted response to these episodes.

One key limitation of depth is that it does not consider the spread between quoted price tiers, including the inside bid-ask spread, and as such does not directly capture the cost aspect of liquidity. Another drawback is that market participants often do not reveal the full quantities they are willing to transact at a given price, so that measured depth may underestimate true depth. Conversely, because of the speed with which orders can be withdrawn from the market, actual depth may instead be lower than what is posted in the limit order book.

A popular liquidity measure, suggested by Kyle (1985) considers the rise (fall) in price that

[11] The minimum tick size is 1/2 of a 32nd of a point for the 10-year note (where a point equals one percent of par) and 1/4 of a 32nd for the 2- and 5-year notes. Using BrokerTec tick data for 2010-2011, Fleming, Mizrach, and Nguyen (2017) find that 97% of quotes for the on-the-run 2-year note are at the minimum tick size.

[12] As noted earlier, GovPX depth is only available from July 1994.

typically occurs with a buyer-initiated (seller-initiated) trade. The "kyle lambda", or price impact, is defined as the slope of the line that relates the price change to trade size and is often estimated by regressing price changes on net signed trading volume (positive for buyer-initiated volume and negative for seller-initiated volume) for intervals of fixed time. The measure is relevant to those executing large trades or a series of trades and, together with the bid-ask spread and depth measures, provides a fairly complete picture of market liquidity.

We calculate price impact for each security and day as the coefficient from a regression of five-minute price changes on contemporaneous net order flow. Price changes are calculated using the midpoint of the last bid and offer quotes posted in a five-minute interval and net order flow is calculated as the number of buyer-initiated trades less the number of seller-initiated trades.[13] Since trade direction is included in the GovPX and BrokerTec databases, we can sign trades unambiguously.[14] As with the bid-ask spreads and depth, the measure is calculated for New York trading hours only.

Daily price impact coefficients are plotted in the bottom panel of Figure 2, and summary statistics are reported in Table 3. Average price impact coefficients for the full sample are 10.6 basis points per 100 hundred net trades for the 2-year note, 23.9 for the 5-year note, and 41.0 for the 10-year note. Price impact tends to be higher during the GovPX sample period than during the BrokerTec sample period, especially in 1999 and 2000 when GovPX data coverage is limited. For the BrokerTec sample period, price impact rises sharply during the 2007-09 financial crisis,

[13] The regressions using net trading frequency tend to have greater explanatory power than those using net trading volume. This may reflect the fact that trade size is exogenous – depending on trading conditions – and that the informativeness of amounts executed during workups tends to be less than that of initial trades, as shown in Fleming and Nguyen (2013).

[14] Two factors complicate this process for BrokerTec data before April 8, 2002. First, before this date, our BrokerTec data does not indicate the aggressive side of each trade. Over this period, we sign trades by comparing the trade price to the state of our derived BrokerTec orderbook just before the trade. If the trade price matches the best ask (bid) price at that time, then the trade is signed as an aggressive buy (sell). For trades where this method does not yield a definitive aggressive side, we look to see which side of the orderbook had quantity removed as part of the trade, then label the opposite side as aggressive. Second, the issue described in footnote 10 means that net trade frequency per workup is not defined prior to April 8, 2002. As in our trade frequency adjustments, we calculate an alternate price impact measure over our BrokerTec sample that defines a single trade in a security as any instance of trading. For the period April 8, 2002 - December 31, 2003, when both this measure and the measure based on workup-delineated trades can be computed, we calculate the average daily ratio of the two for each security. For January 2, 2001 - April 5, 2002, the daily price impact measure becomes the price impact from the trade instance definition, scaled up by this average ratio. Note that this adjustment is made prior to the market coverage adjustments of footnote 9.

and to a lesser extent during the 2013 taper tantrum and around the October 2014 flash rally.

We report the correlation coefficients of each liquidity measure across the 2-, 5-, and 10-year notes in Table 4. The table shows that better liquidity in one security tends to be associated with better liquidity in another. The association is strongest between the 5- and 10-year notes. For these two maturities, correlations range from 74-90% for bid-ask spreads, depth, and price impact. By contrast, the correlations between the 2- and 10-year notes for these variables range from 49-64%, suggesting that liquidity dynamics for the 2-year note are somewhat separate from those for the longer maturities. A similar distinction appears to hold for trading frequency and volume.

We also report correlations across our various liquidity measures in Table 5. The correlations are of daily averages across the 2-, 5-, and 10-year notes. The analysis reveals that better liquidity by one measure tends to be associated with better liquidity in another, so bid-ask spreads and price impact are positively correlated with one another, and both negatively correlated with depth. Increases in the trading activity measures, and especially trade size, also tend to be associated with better liquidity. Interestingly, the correlations between bid-ask spreads and the depth and price impact measures are smaller in magnitude in the latter part of the sample, perhaps reflecting the spread's limited variation over this period.

4.2 Comparison with CRSP

Existing longer-term studies of Treasury transaction costs have used CRSP bid-ask spreads. Until 1996, CRSP's source for Treasury price quotes was the "Composite 3:30 P.M. Quotations for US Government Securities" compiled by the Federal Reserve Bank of New York. Starting in October of 1996, CRSP's source for Treasury price quotes switched to GovPX, which provides a daily 5 p.m. aggregation of intra-day bids, offers, and transactions.[15]

Figure 3 plots CRSP bid-ask spreads for the 2-, 5-, and 10-year notes against those from GovPX and BrokerTec. Each panel in the figure shows that the GovPX/BrokerTec and CRSP bid-ask spread series have very little in common. For the period from late June 1998 to early February 2009, the CRSP series are nearly constant. The CRSP series actually narrow in late

[15] See http://www.crsp.com/files/treasury_guide_0.pdf.

June 1998, right before liquidity worsened with the near-failure of LTCM. The spreads then remained steady through the LTCM episode, the September 11 attacks, and the late 2008 peak of the 2007-09 financial crisis. CRSP bid-ask spread variation resumed in February 2009, but even then bears little resemblance to our BrokerTec series.

Table 6 confirms the lack of clearly signed correlation between our GovPX/BrokerTec bid-ask spreads and the CRSP spreads. Not only are the correlations not close to one, but they are frequently close to zero or negative, with 17 of the 36 coefficients in the table less than zero. The weak correlations occur regardless of estimation approach, be it daily levels, daily changes, or monthly changes of exponentially-weighted moving averages.

In terms of magnitudes, the CRSP bid-ask spreads imply significantly higher costs to execute trades. The 2-, 5-, and 10-year notes all show CRSP spreads to frequently be two 32nds of a point in the early- to mid-1990s, almost four times wider than the spreads we record from the intraday GovPX data over the same period. CRSP spreads during the BrokerTec era are somewhat narrower, albeit still multiples of the BrokerTec spreads. That said, spreads may vary across different parts of the market (be it the interdealer market or the dealer-to-customer market), so it is probably the lack of positive correlation in the spreads which is most surprising.

It turns out that an important reason for the spread differences is that CRSP seems to be relying on indicative bid-ask spreads from GovPX, whereas our analysis relies on market spreads. That is, the GovPX database contains both market quotes, which reflect actual quotes submitted by market participants, and indicative quotes, which reflect model-based estimates of prices. When we instead pull end-of-day (5 p.m.) indicative quotes from GovPX, our series matches the CRSP series perfectly for much of the sample.[16]

Another possible reason for the divergences in the spread series could be time-of-day differences. CRSP reports end-of-day spreads, whereas we report averages based on quotes throughout the day. However, if we instead pull end-of-day market quotes from GovPX and BrokerTec, we essentially get a noiser and more discrete version of our average series and not anything looking like the CRSP series. Overall, our findings cast doubt on the value of the information contained in CRSP bid-ask spreads over our sample period.

[16]Specifically, the quotes match on nearly every day from October 1996 to May 2005. After May 2005, there is variation in the CRSP series that does not match our indicative GovPX quotes.

In an earlier paper, Duffee (1996) reports that CRSP bid-ask spreads have at times been based on a maturity-dependent "spread curve" that does not change from day to day. That paper was written at a time when CRSP spreads came from the Federal Reserve Bank of New York. Our findings show that the spreads in CRSP since it switched to GovPX in October 1996 exhibit similar behavior.

4.3 Liquidity Index

To summarize the evolution of Treasury market liquidity from 1991 to 2017, we construct a liquidity index, combining the bid-ask spread, depth, and price impact measures. The rationale for combining the measures is that no single measure suitably measures liquidity by itself because each captures a different aspect of liquidity. Bid-ask spreads thus measure the cost aspect of liquidity (for single trades of limited size), order book depth the quantity of securities that can be transacted (at the inside spread), and price impact the extent to which prices move in response to trades, thereby measuring both cost and quantity aspects of liquidity.

To facilitate combining the measures into a single index, it is convenient to first invert depth. The transformed depth measure has better statistical properties. Moreover, in periods of illiquidity, bid-ask spreads, price impact, and 1/depth will all tend to rise, which allows us to use positive index weights for all index components.

Before creating the index, we impute the measures for dates the underlying variables are missing because of data limitations, primarily depth before July 1994, but also occasional days for any of the measures. To do this, for each security (2-, 5-, and 10-year note) and sub-sample (GovPX and BrokerTec), we first project each measure onto the MOVE Index and the VIX Index, excluding the 1999-2004 period of limited data coverage. With three securities, two subsamples, and three liquidity measures, this amounts to running 18 separate regressions.[17] Then, for any dates with missing data, we use the results from the aforementioned models to predict each of the measures.

The next step in index construction is to standardize each of the liquidity measures for each security to have mean zero and variance one. We then construct an index for each measure,

[17]These regression results are excluded from the paper for brevity but are available from the authors on request.

through a simple averaging across the three notes, as well as an index for each note, through a simple averaging across the three measures. We then create an overall Treasury liquidity index by averaging across the measure-specific or security-specific indexes (results are the same regardless of which set of indexes are averaged). As a final step, we exponentially smooth each liquidity index. Smoothing helps us construct an average that is more reflective of fundamental liquidity for a given day by dampening the influence of announcements, calendar effects, or noise in the estimation process.[18]

The indexes for the various measures are plotted in the top panel of Figure 4 and the indexes for the 2-, 5-, and 10-year notes are plotted in the middle panel of Figure 4. The indexes, which are highly correlated across both measures and securities, tend to be lower during the BrokerTec sample period, likely reflecting the liquidity benefits of electronic trading and expanded competition in the interdealer market. Aside from some spikes in the early 1990s, the indexes are marked by sharp increases in the fall of 1998 around the near-failure of LTCM, and in late 2008 after the bankruptcy of Lehman Brothers. More recently, the indexes point to increases in illiquidity during the 2013 taper tantrum and around the October 2014 flash rally.

The high correlations across the measure- and security-specific indexes suggest a common factor structure, which we aim to capture by simple averaging. The bottom panel of Figure 4 plots the resulting aggregate liquidity index. Over the 1991 to 2017 sample period, the aggregate liquidity index reveals a significant downward trend, reflecting the combined compression of bid-ask spreads, price impact, and 1/depth over the last 26 years. The data suggest that liquidity in 2017 is good by historical standards.

4.4 Explaining Liquidity Index Variation

Market liquidity is a function of the market structure that allows buyers and sellers of securities to come to a market clearing price. Dealers and HFTs play a crucial role, as these institutions intermediate between buyers and sellers. The ability of the market making sector to intermediate in turn depends on its ability to obtain funding. For example, during times of market turmoil

[18] Compared to a simple moving average, exponentially declining weights prevent observations from the more distant past of having undue influence when they drop out of the simple moving average window. For our liquidity indices, we set the smoothing parameter to ensure that 95% of the weights cover observations over the most recent 21 days.

or crisis, one would expect market makers to have difficulty raising funds, which in turn affects their ability to make markets.

In fact, economic theory suggests a close link between market liquidity and funding liquidity (see Brunnermeier and Pedersen (2009)). When a volatility shock occurs, lenders may tighten their terms of funding in the form of higher haircuts and repo rates. As funding becomes scarce, market makers find it more difficult to obtain leverage to finance their inventories. Market liquidity can therefore decline, which leads to higher price impact and higher volatility. There is therefore a self reinforcing feedback mechanism linking volatility shocks, funding liquidity, and market liquidity. Consistent with such theories, Adrian, Etula, and Muir (2014) document that the risk premia across stocks and bonds are systematically related to dealer leverage shocks, which the authors use as a proxy for the availability of funding liquidity (as more ample funding liquidity allow dealers to increase leverage).

While these theories can potentially be applied in a variety of asset classes, we argue that the link between volatility, funding liquidity, and market liquidity may be especially strong for Treasuries. Because of their extraordinary safety, demand for Treasuries rises during a flight-to-quality or "risk-off" episode, which can potentially increase the demand for immediacy. The increased demand for immediacy, in turn, puts strains on the market making sector, and hence on market liquidity. Furthermore, Treasuries are used extensively as collateral and may therefore be used for funding in repo markets. The twin uses of Treasuries as a safe haven during times of stress and as a source of immediate funding imply that Treasuries as an asset class should display especially tight links between volatility, funding liquidity, and market liquidity. We investigate this conjecture by studying the link between volatility, funding liquidity, and our market liquidity index empirically.

Figure 5 shows strong contractions in the funding liquidity measures during both the LTCM episode and the financial crisis. The top left panel, for example, reveals sharp widenings of the Baa/Treasury spread, which can be interpreted as increases in the convenience yield offered by Treasuries over securities with similar credit quality (Krishnamurthy and Vissing-Jorgensen (2012)). The top right panel shows that the on-the-run/off-the-run spread underwent similar crisis dynamics as the market liquidity index, with heightened illiquidity also occurring in the late 1990s and early 2000s.

The middle left panel of Figure 5 plots the liquidity index together with the Refcorp-Treasury spread, which is advocated by Longstaff (2004) as an indicator of funding liquidity. The time series plot shows strong covariation between market and funding liquidity, though the Refcorp spread exhibits a low frequency upward trend over the sample period while the market liquidity index shows a low frequency downward trend.

The middle right panel of Figure 5 plots the average Treasury spline error, which is advocated as a funding liquidity measure by Hu, Pan, and Wang (2013) (also see Fleming (2000)). In an arbitrage-free yield curve, Treasuries with neighboring maturities have similar cash flows and must therefore command similar prices. Dispersion around a smooth curve is therefore interpreted as an arbitrage opportunity which may not be realized when arbitrage capital is scarce. The fit errors mainly show a correlation to market liquidity during the 2007-09 crisis, and to some extent during the fall 1998 financial market turmoil, around the September 11 attacks, and during the 2013 taper tantrum, but otherwise co-vary little with market liquidity.

The bottom panel of Figure 5 plots the swap spread and the TED spread. The swap spread (which is an average of the 2-, 5-, and 10-year swap spreads) widened sharply during the LTCM episode and in late 2007 and much of 2008, but then narrowed in late 2008 and 2009. In fact, the link between the swap spread and funding liquidity is ambiguous. A flight to quality leads to a compression of Treasury yields, widening the spread, but a decline in funding liquidity removes balance sheet capacity to arbitrage the interest rate basis, which can allow the spread to narrow or even go negative. The TED spread, the difference between unsecured short term funding and short-term Treasury yields, also widens mainly in the fall 1998 and 2007-09 crises.

4.5 Evidence from Regressions

Our graphical evidence suggests that the six different metrics of funding liquidity co-move with market liquidity in a way that is state dependent. During times of market turmoil and high volatility, such as the 1998 LTCM episode and the 2007-09 financial crisis, funding liquidity and market liquidity appear to co-move. This co-movement is less pronounced outside of high volatility periods. We investigate this observation by regressing the market liquidity index onto both the funding liquidity variables, the aggregate volatility variables, and their interactions.

Table 7 reports regressions of the change in the market liquidity index on the change of each of the funding liquidity measures at a monthly frequency. We regress in differences to address the trend in the liquidity index and the apparent persistence of some of the funding measures. The table shows that all six funding liquidity variables are significantly and positively related to market liquidity. The largest adjusted R^2 of 12% is attained by both the on-the-run/off-the-run spread and the swap spread. When combined, shocks to the six funding measures are able to explain 21% of the monthly changes in market liquidity. In the combined regression, the on-the-run/off-the-run spread, swap spread, spline error and TED spread remain significant, whereas the Baa spread and Refcorp spread lose significance.

Turning next to the volatility measures (which are plotted in Figure 6), Table 8 shows that shocks to the the MOVE index, realized volatility, and the VIX index each help explain monthly changes in the liquidity index. The largest adjusted R^2 value falls on realized volatility (66%). When the volatility measures are combined, only realized volatility remains significant, with a joint R^2 of 66%.

Finally, we test the hypothesis that funding liquidity is most closely related to market liquidity during times of turmoil. To do so, we run regressions of the market liquidity index on each of the funding measures, in addition to interaction terms of the change in each funding liquidity measure with the level of realized volatility. We leave realized volatility in levels to preserve the interpretation that the coefficient on the funding liquidity variable is a linear function of volatility.[19] That is, we estimate

$$\Delta MarketLiq_t = \alpha + (\beta_0 + \beta_1 \, RV_t)\Delta FundingLiq_t + \varepsilon_t$$

for each of the six funding liquidity variables.

Table 9 shows that among the six variables that were previously identified as significantly related to market liquidity, four interact significantly with realized volatility. In particular, the market liquidity index appears to load on the Baa spread, on-the-run/off-the-run spread, Refcorp

[19] We de-mean realized volatility and the change in funding liquidity in order to make the coefficients comparable to the single variable regressions in the preceding tables.

spread, and swap spread in a way that strengthens in times of high realized volatility. These regressions therefore seem to confirm the visual evidence from Figure 5 that the relationship between funding liquidity and market liquidity is strongest at times of high volatility.

5 Conclusion

The paper presents a daily liquidity index for the U.S. Treasury securities market for a 26-year sample period (1991-2017). The index is constructed from order book and transactions data for the on-the-run 2-, 5-, and 10-year securities, aggregating information from intraday bid-ask spreads, depth, and price impact. To our knowledge, this is the first time a U.S. Treasury market liquidity index has been constructed in the literature using actual order book and transactions data.

As noted, extant papers have relied on bid-ask spread data from CRSP to generate long time series of Treasury liquidity. Interestingly, we find very little correlation between our bid ask spread series and those of CRSP. Further investigation suggests that CRSP relies on indicative end-of-day quotations, whereas our bid-ask spreads are based on actual order book data. The fact that the CRSP series are largely uncorrelated with ours, and that they remained unchanged for years through the depths of the 2007-09 financial crisis, suggests that they have little informational value over our sample period.

We study the properties of our liquidity index by relating them to market volatility and funding liquidity metrics. Treasury market liquidity is closely related to market volatility: in times of high volatility, market liquidity tends to evaporate. Those are also the times when funding liquidity metrics tend to be most closely correlated with market liquidity. In particular, during the 1998 LTCM episode and the 2007-09 financial crisis, funding liquidity deteriorated sharply at the same time as market liquidity evaporated. Some funding liquidity indicators also deteriorated following the September 11, 2001 attacks and during the 2013 taper tantrum, both times when market liquidity was poor.

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Table 1: Trading Activity Summary Statistics

Panel A: GovPX Sample (June 1991-December 2000)			
	2-Year	5-Year	10-Year
Trading volume	5.08	5.03	3.27
	(2.52)	(2.41)	(1.59)
Trade frequency	387.18	638.53	567.36
	(162.63)	(268.46)	(232.47)
Trade size	12.87	7.74	5.59
	(2.41)	(1.26)	(1.04)

Panel B: BrokerTec Sample (Jan 2001-December 2017)			
	2-Year	5-Year	10-Year
Trading volume	22.37	31.29	26.99
	(14.69)	(18.13)	(15.78)
Trade frequency	762.03	2063.56	2115.06
	(553.55)	(1130.57)	(1136.81)
Trade size	31.48	15.55	12.69
	(9.80)	(4.95)	(3.87)

Panel C: Full Sample (June 1991-December 2017)			
	2-Year	5-Year	10-Year
Trading volume	16.15	21.85	18.45
	(14.47)	(19.27)	(17.03)
Trade frequency	627.22	1551.31	1558.12
	(487.93)	(1145.51)	(1182.60)
Trade size	24.79	12.74	10.13
	(11.97)	(5.51)	(4.65)

Source: Authors' calculations, based on data from BrokerTec and GovPX.
Notes: The table reports means and standard deviations (in parentheses) of daily trading volume, daily trade frequency, and average daily trade size for the on-the-run 2-, 5-, and 10-year Treasury notes from June 17, 1991 to December 29, 2017. Trading volume is in billions of dollars (par value) and trade size is in millions of dollars (par value).

Table 2: Funding Liquidity and Volatility Summary Statistics

Panel A: Funding Liquidity				
	Mean	Std Dev	Min	Max
Baa spread	2.400	0.768	1.220	6.160
On-the-run spread	0.142	0.109	-0.043	0.654
Refcorp spread	0.268	0.202	-0.150	1.536
Spline error	0.026	0.021	0.007	0.228
Swap spread	0.378	0.236	-0.081	1.225
TED spread	0.479	0.371	0.090	4.580

Panel B: Volatility				
	Mean	Std Dev	Min	Max
MOVE index/100	0.948	0.268	0.440	2.646
Realized volatility	2.468	1.351	0.027	14.612
VIX index/100	0.192	0.080	0.091	0.809

Source: Authors' calculations, based on data from Bloomberg, the Board of Governors of the Federal Reserve System, BrokerTec, the Federal Reserve Bank of St Louis, GovPX, and Haver.

Notes: The table reports descriptive statistics for various funding liquidity indicators (Panel A) and volatility measures (Panel B). All variables are measured daily from June 17, 1991 to December 29, 2017 (although spline error is only available to March 31, 2016). All variables except the indices are measured in percent.

Table 3: Liquidity Summary Statistics

Panel A: GovPX Sample (June 1991-December 2000)			
	2-Year	5-Year	10-Year
Bid-ask spread	0.78	1.32	2.43
	(0.27)	(0.38)	(0.60)
Depth	64.74	30.63	22.79
	(21.87)	(6.94)	(6.46)
Price impact	16.77	31.29	54.49
	(7.72)	(11.80)	(19.46)

Panel B: BrokerTec Sample (Jan 2001-December 2017)			
	2-Year	5-Year	10-Year
Bid-ask spread	0.84	0.90	1.79
	(0.16)	(0.24)	(0.46)
Depth	654.90	100.63	87.74
	(521.00)	(50.39)	(40.47)
Price impact	7.07	19.76	33.32
	(5.66)	(12.18)	(17.34)

Panel C: Full Sample (June 1991-December 2017)			
	2-Year	5-Year	10-Year
Bid-ask spread	0.82	1.05	2.02
	(0.20)	(0.36)	(0.60)
Depth	494.03	81.54	70.01
	(516.38)	(53.21)	(45.16)
Price impact	10.60	23.91	40.96
	(7.99)	(13.26)	(20.79)

Source: Authors' calculations, based on data from BrokerTec, the Federal Reserve Bank of New York, GovPX, and Haver.

Notes: The table reports means and standard deviations (in parentheses) of average daily bid-ask spread, average daily order book depth at the inside spread (bid plus offer side), and daily price impact for the on-the-run 2-, 5-, and 10-year Treasury notes from June 17, 1991 to December 29, 2017. Price impact is estimated as the slope coefficient from a regression of five-minute price changes on the net number of trades over the same five-minute interval. Bid-ask spread is in basis points in return space, so one basis point equals one one hundredth of a percent of price (with price measured as the bid-ask midpoint), depth is in millions of dollars (par value) and price impact is in basis points per 100 net trades.

Table 4: Correlations of Individual Liquidity/Activity Measures Across Securities

Panel A: Bid-Ask Spread			
	2-Year	5-Year	10-Year
2-year	1.000	0.578	0.494
5-year	0.578	1.000	0.863
10-year	0.494	0.863	1.000
Panel B: Depth			
	2-Year	5-Year	10-Year
2-year	1.000	0.813	0.638
5-year	0.813	1.000	0.896
10-year	0.638	0.896	1.000
Panel C: Price Impact			
	2-Year	5-Year	10-Year
2-year	1.000	0.733	0.622
5-year	0.733	1.000	0.740
10-year	0.622	0.740	1.000
Panel D: Trading Volume			
	2-Year	5-Year	10-Year
2-year	1.000	0.691	0.655
5-year	0.691	1.000	0.973
10-year	0.655	0.973	1.000
Panel E: Trade Frequency			
	2-Year	5-Year	10-Year
2-year	1.000	0.701	0.620
5-year	0.701	1.000	0.979
10-year	0.620	0.979	1.000
Panel F: Trade Size			
	2-Year	5-Year	10-Year
2-year	1.000	0.852	0.884
5-year	0.852	1.000	0.932
10-year	0.884	0.932	1.000

Source: Authors' calculations, based on data from BrokerTec, the Federal Reserve Bank of New York, GovPX, and Haver.
Notes: The table reports correlation coefficients of the levels of individual liquidity/activity measures across securities for the on-the-run 2-, 5-, and 10-year Treasury notes from June 17, 1991 to December 29, 2017.

Table 5: Correlations Across Liquidity/Activity Measures

Panel A: GovPX Sample (June 1991-December 2000)						
	Bid-Ask Spread	Depth	Price Impact	Trading Volume	Trade Fre- quency	Trade Size
Bid-ask spread	1.000	-0.703	0.797	-0.159	-0.099	-0.309
Depth	-0.703	1.000	-0.602	0.105	-0.045	0.571
Price impact	0.797	-0.602	1.000	0.031	0.070	-0.225
Trading volume	-0.159	0.105	0.031	1.000	0.944	0.588
Trade frequency	-0.099	-0.045	0.070	0.944	1.000	0.338
Trade size	-0.309	0.571	-0.225	0.588	0.338	1.000
Panel B: BrokerTec Sample (Jan 2001-December 2017)						
	Bid-Ask Spread	Depth	Price Impact	Trading Volume	Trade Fre- quency	Trade Size
Bid-ask spread	1.000	-0.262	0.486	-0.316	-0.257	-0.165
Depth	-0.262	1.000	-0.459	0.137	-0.069	0.554
Price impact	0.486	-0.459	1.000	0.065	0.271	-0.337
Trading volume	-0.316	0.137	0.065	1.000	0.824	0.388
Trade frequency	-0.257	-0.069	0.271	0.824	1.000	-0.119
Trade size	-0.165	0.554	-0.337	0.388	-0.119	1.000
Panel C: Full Sample (June 1991-December 2017)						
	Bid-Ask Spread	Depth	Price Impact	Trading Volume	Trade Fre- quency	Trade Size
Bid-ask spread	1.000	-0.347	0.717	-0.462	-0.409	-0.435
Depth	-0.347	1.000	-0.539	0.432	0.246	0.712
Price impact	0.717	-0.539	1.000	-0.334	-0.178	-0.558
Trading volume	-0.462	0.432	-0.334	1.000	0.892	0.704
Trade frequency	-0.409	0.246	-0.178	0.892	1.000	0.400
Trade size	-0.435	0.712	-0.558	0.704	0.400	1.000

Source: Authors' calculations, based on data from BrokerTec, the Federal Reserve Bank of New York, GovPX, and Haver.

Notes: The table reports correlation coefficients across the levels of liquidity/activity measures from June 17, 1991 to December 29, 2017. Daily liquidity/activity measures are averages of those for the on-the-run 2-, 5-, and 10-year notes.

Table 6: Correlations of GovPX/BrokerTec Bid-Ask Spreads with CRSP Bid-Ask Spreads

Panel A: GovPX Sample (June 1991-December 2000)			
	2-Year	5-Year	10-Year
Daily level	0.442	0.308	-0.150
Daily change	0.147	0.128	0.026
Daily level, EWMA	0.583	0.408	-0.201
Monthly change, EWMA	0.008	0.039	0.041
Panel B: BrokerTec Sample (Jan 2001-December 2017)			
	2-Year	5-Year	10-Year
Daily level	-0.127	-0.224	-0.210
Daily change	0.001	-0.004	-0.002
Daily level, EWMA	-0.177	-0.292	-0.261
Monthly change, EWMA	-0.011	-0.014	-0.129
Panel C: Full Sample (June 1991-December 2017)			
	2-Year	5-Year	10-Year
Daily level	0.157	0.238	-0.040
Daily change	0.090	0.071	0.008
Daily level, EWMA	0.205	0.287	-0.046
Monthly change, EWMA	-0.005	0.002	-0.030

Source: Authors' calculations, based on data from from BrokerTec, CRSP, the Federal Reserve Bank of New York, GovPX, and Haver.

Notes: The table reports correlation coefficients of average daily bid-ask spreads from GovPX/BrokerTec and end-of-day bid-ask spreads from CRSP for each of the on-the-run 2-, 5-, and 10-year notes from June 17, 1991 to December 29, 2017. Correlation coefficients are reported for the daily levels of the spreads, daily changes in the spreads, daily levels of the exponentially-weighted moving averages, and monthly changes in the exponentially-weighted moving averages (measured as of the middle of each month).

Table 7: Funding Liquidity Regressions

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Baa spread	0.37**						0.00
	(2.54)						(0.02)
On-the-run spread		2.44***					1.32**
		(4.00)					(2.23)
Refcorp spread			0.59**				0.26
			(2.50)				(1.00)
Swap spread				1.81***			1.10*
				(3.38)			(1.93)
Spline error					8.71**		5.04*
					(2.32)		(1.96)
TED spread						0.33***	0.14**
						(5.16)	(2.24)
Constant	-0.01	-0.00	-0.01	-0.00	-0.00	-0.00	-0.00
	(-0.56)	(-0.46)	(-0.57)	(-0.22)	(-0.47)	(-0.50)	(-0.20)
Adj R^2	0.05	0.12	0.03	0.12	0.07	0.08	0.21
N	318	318	318	318	297	318	297

Source: Authors' calculations, based on data from Bloomberg, BrokerTec, the Board of Governors of the Federal Reserve System, the Federal Reserve Banks of New York and St Louis, GovPX, and Haver.
Notes: This table reports time series regressions of the market liquidity index onto various funding liquidity indicators. The reported regressions are in monthly changes. Newey-West t-statistics are in parentheses, with lag length $T^{1/3}$, where T is the indicated sample size.
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 8: Volatility Regressions

	(1)	(2)	(3)	(4)
Move index/100	1.18***			0.09
	(5.28)			(0.63)
RV		0.41***		0.39***
		(11.13)		(9.64)
VIX index/100			1.80***	0.10
			(4.61)	(0.37)
Constant	-0.00	-0.01	-0.00	-0.01
	(-0.52)	(-0.87)	(-0.52)	(-0.83)
Adj R^2	0.37	0.66	0.08	0.66
N	318	318	318	318

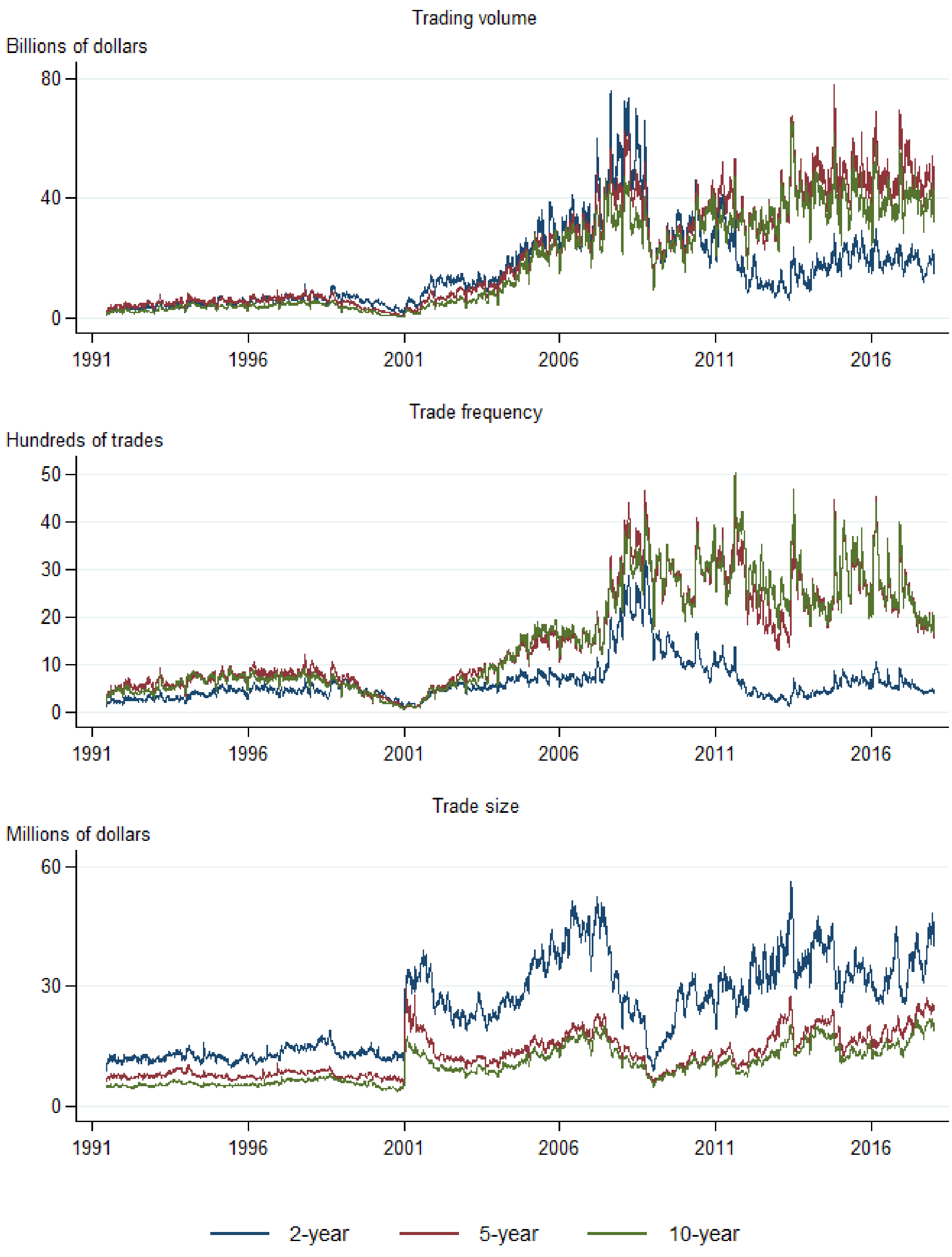
Source: Authors' calculations, based on data from BrokerTec, the Federal Reserve Banks of New York and St Louis, GovPX, and Haver.
Notes: This table reports time series regressions of the market liquidity index onto various volatility indicators. The reported regressions are in monthly changes. Newey-West t-statistics are in parentheses, with lag length $T^{1/3}$, where T is the indicated sample size.
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 9: Funding Liquidity and Volatility Interaction Regressions

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Baa spread	0.21						0.10
	(1.46)						(0.83)
Baa spread * RV	0.12***						-0.10
	(4.13)						(-0.85)
On-the-run spread		1.74***					1.08*
		(3.22)					(1.89)
On-the-run spread * RV		0.79**					0.38
		(2.34)					(0.52)
Refcorp spread			0.40*				0.30
			(1.73)				(1.20)
Refcorp spread * RV			0.35***				0.01
			(3.89)				(0.04)
Swap spread				0.85**			0.38
				(2.01)			(0.90)
Swap spread * RV				1.02**			0.85
				(2.44)			(1.21)
Spline error					5.02		2.49
					(1.30)		(0.76)
Spline error * RV					2.41		1.77
					(1.17)		(0.89)
TED spread						0.29**	0.25*
						(2.59)	(1.81)
TED spread * RV						0.02	-0.10
						(0.64)	(-1.30)
Constant	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01
	(-1.02)	(-1.28)	(-1.02)	(-0.83)	(-0.87)	(-0.56)	(-0.72)
Adj R^2	0.06	0.15	0.05	0.17	0.07	0.08	0.23
N	318	318	318	318	297	318	297

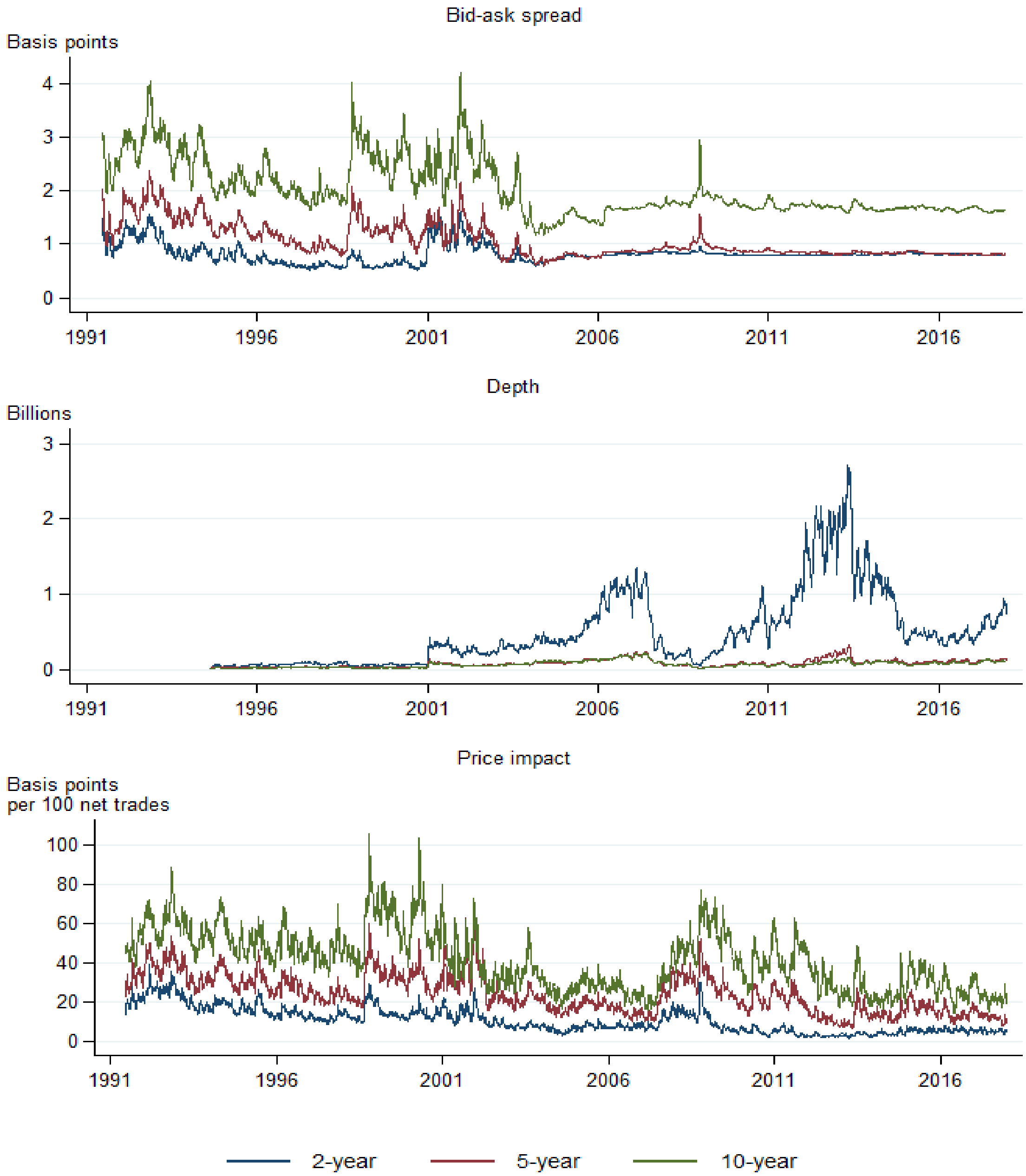
Source: Authors' calculations, based on data from Bloomberg, BrokerTec, the Board of Governors of the Federal Reserve System, the Federal Reserve Banks of New York and St Louis, GovPX, and Haver.
Notes: This table reports time series regressions of the market liquidity index onto various funding liquidity measures interacted with realized volatility (RV), the inverse maturity-weighted average realized volatility across the 2-, 5-, and 10-year notes. The reported regressions are in monthly changes. Newey-West t-statistics are in parentheses, with lag length $T^{1/3}$, where T is the indicated sample size.
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Figure 1: Trading Activity Metrics



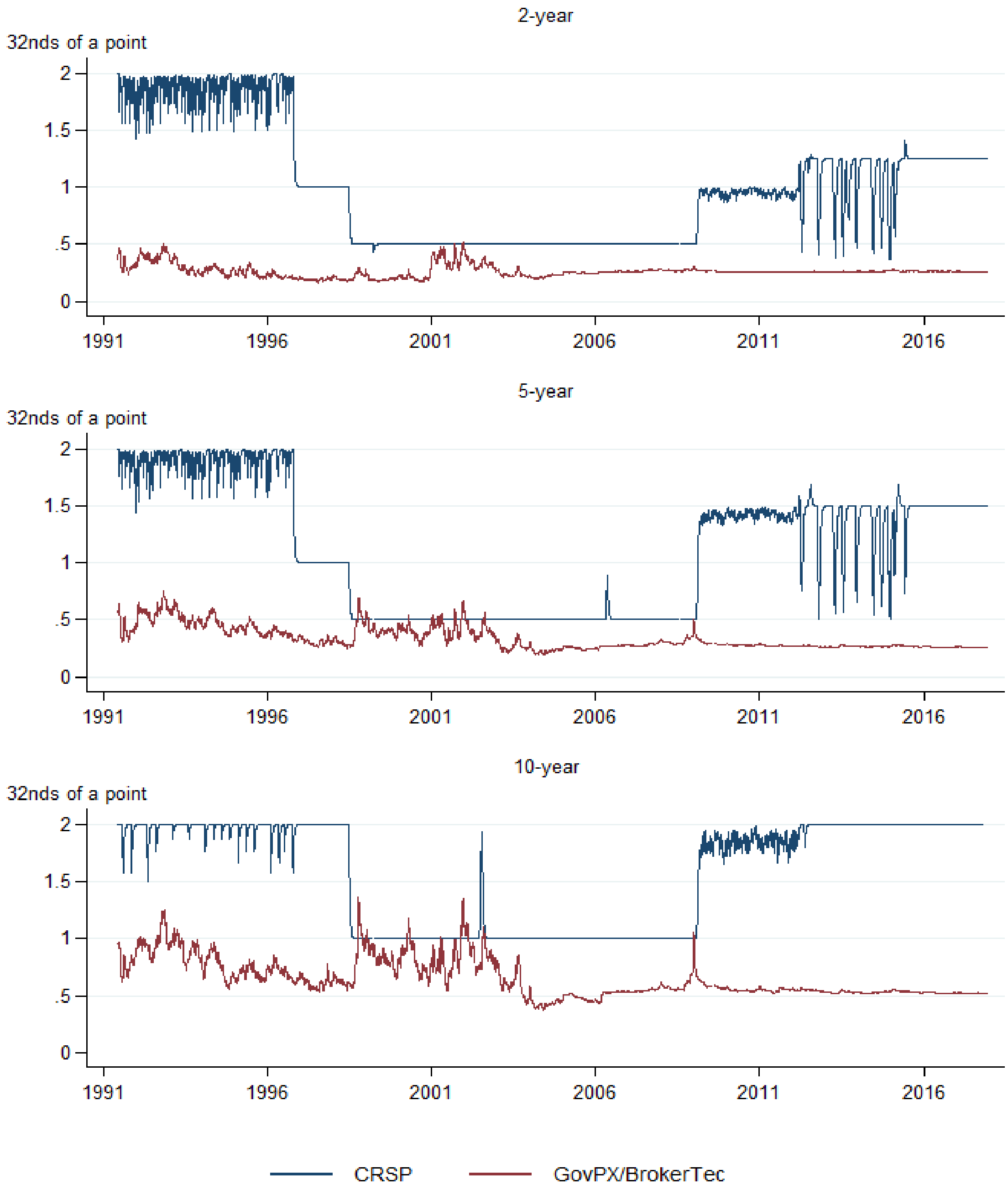
Source: Authors' calculations, based on data from BrokerTec and GovPX.
Notes: The figure plots trading volume, trade frequency, and average trade size by day from June 17, 1991 to December 29, 2017. Plotted lines are exponentially-weighted moving averages.

Figure 2: Liquidity Metrics



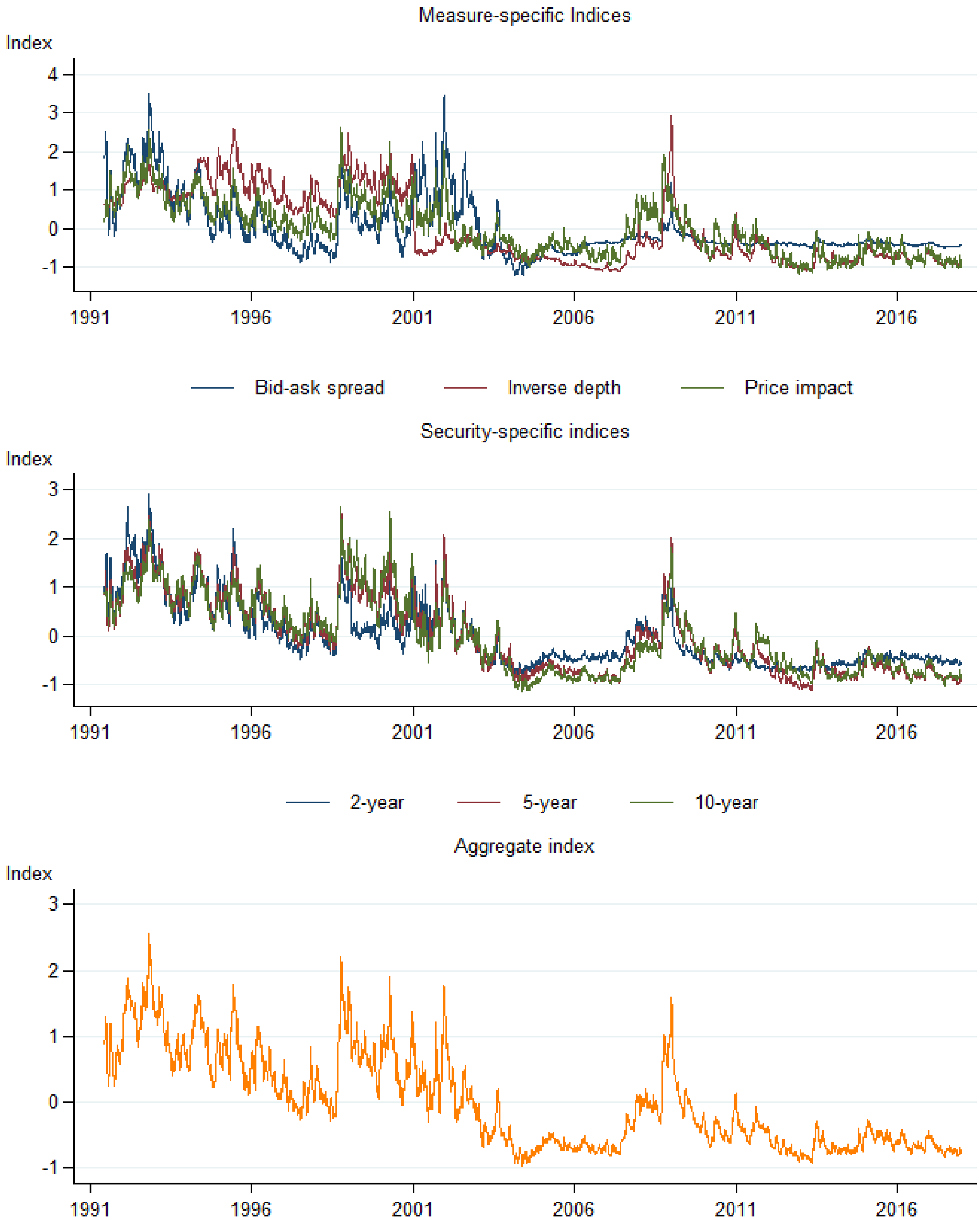
Source: Authors' calculations, based on data from BrokerTec, the Federal Reserve Bank of New York, GovPX, and Haver.
Notes: The figure plots average bid-ask spread, average order book depth at the inside spread (bid plus offer side), and price impact by day from June 17, 1991 to December 29, 2017. Price impact is estimated as the slope coefficient from a regression of five-minute price changes on the net number of trades over the same five-minute interval. Basis points are measured in return space, so one basis point equals one one hundredth of a percent of price (with price measured as the bid-ask midpoint). Plotted lines are exponentially-weighted moving averages.

Figure 3: GovPX/BrokerTec vs. CRSP Bid-Ask Spreads



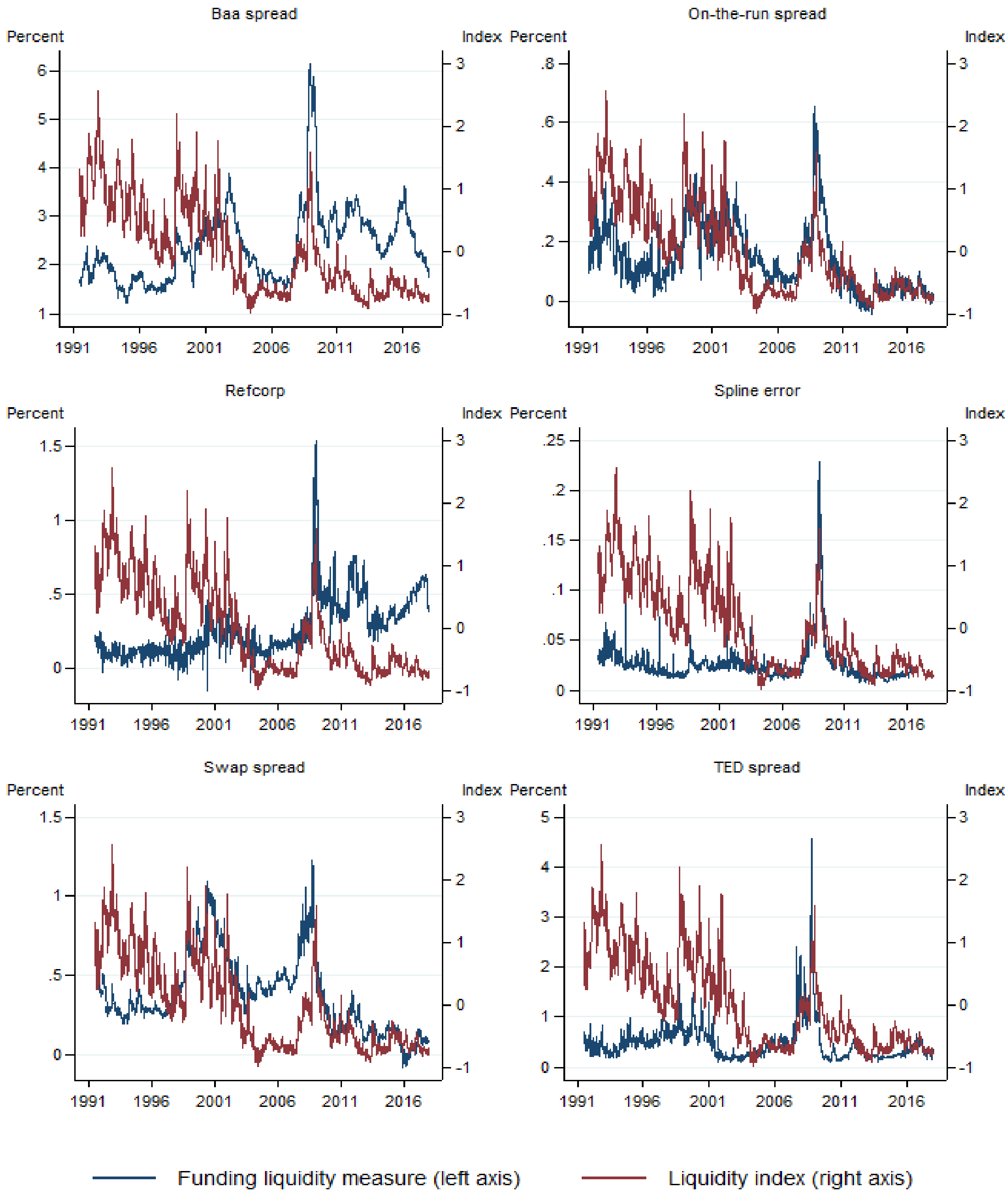
Source: Authors' calculations, based on data from BrokerTec, CRSP, the Federal Reserve Bank of New York, GovPX, and Haver.
Notes: The figure plots average daily bid-ask spreads from GovPX/BrokerTec and end-of-day spreads from CRSP from June 17, 1991 to December 29, 2017. Spreads are measured in 32nds of a point, where a point equals one percent of par. Plotted lines are exponentially-weighted moving averages.

Figure 4: Liquidity Index



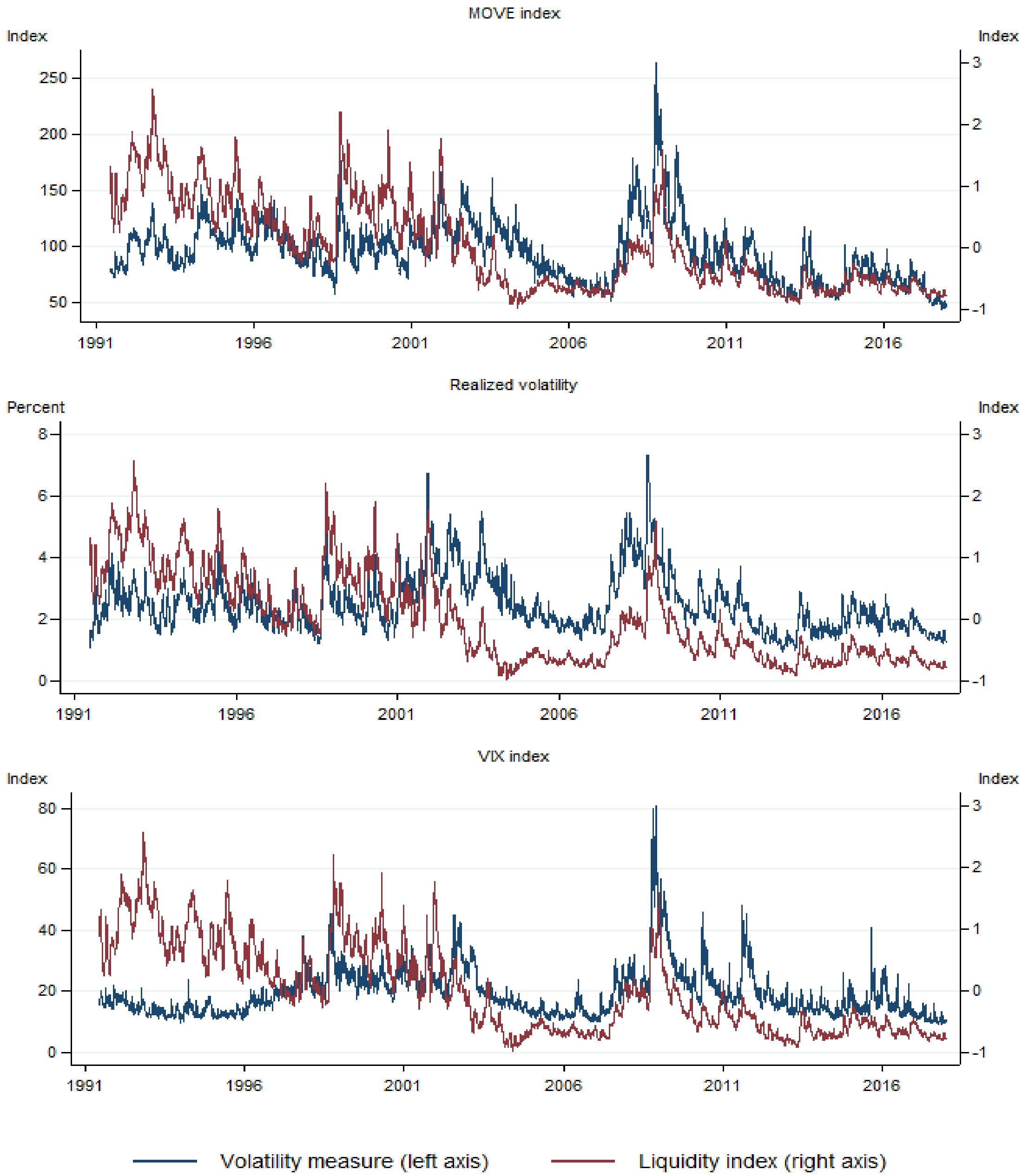
Source: Authors' calculations, based on data from BrokerTec, the Federal Reserve Bank of New York, GovPX, and Haver.
Notes: The figure plots measure-specific and security-specific liquidity indices and the aggregate liquidity index by day from June 17, 1991 to December 29, 2017. The measure-specific indices are the average of the indicated standardized liquidity series across the 2-, 5-, and 10-year securities. The security-specific indices are averages of the standardized bid-ask spread, depth, and price impact series. The aggregate index is the average of the specific indices. Plotted lines are exponentially-weighted moving averages.

Figure 5: Funding Liquidity Series



Source: Authors' calculations, based on data from Bloomberg, the Board of Governors of the Federal Reserve System, BrokerTec, the Federal Reserve Banks of New York and St Louis, GovPX, and Haver.
Notes: The figure plots various funding liquidity indicators against the Treasury market liquidity index by day from June 17, 1991 to December 29, 2017. The liquidity index is plotted as an exponentially-weighted moving average.

Figure 6: Volatility Series



Source: Authors' calculations, based on data from the Board of Governors of the Federal Reserve System, BrokerTec, the Federal Reserve Banks of New York and St Louis, GovPX, and Haver.

Notes: The figure plots various volatility series against the Treasury market liquidity index from June 17, 1991 to December 29, 2017. Realized volatility is calculated as the inverse maturity-weighted average of realized volatility for the 2-, 5-, and 10-year notes. The liquidity index and realized volatility show exponentially-weighted moving averages of daily observations. All other series show daily observations.