# The Microstructure of a U.S. Treasury ECN: The BrokerTec Platform*


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First draft: April 2, 2007
This draft: July 13, 2009



**Abstract**

This paper assesses the microstructure of the U.S. Treasury securities market using tick data from the BrokerTec electronic trading platform. We examine trading activity, bid-ask spreads, and depth for the on-the-run 2-, 3-, 5-, 10- and 30-year securities and find that liquidity is markedly greater than that reported by earlier studies using data from GovPX. We analyze the price impact of trades and find that the effects are overstated if order book changes are ignored, and that order book changes affect prices by themselves. We also explore a novel feature of this platform – the ability to enter "iceberg" orders – and find that such orders are more common when price volatility is higher, as predicted by theory.



**Keywords**: microstructure; Treasury market; bid-ask spread; price impact; hidden orders;

**JEL Codes**: G14; G12; D4; C32;



* We thank Bruno Biais, Peter Dunne, Sergio Ginebri, Frank de Jong, Carol Osler, Jennifer Roush and seminar participants at the Bank of Canada, 3rd Annual Central Bank Conference on the Microstructure of Financial Markets, Federal Reserve System Conference on Financial Markets & Institutions, Fourth MTS Conference on Financial Markets, and the University of Cambridge conference on High Frequency Dynamics and Bond Markets for helpful comments. We thank Nicholas Klagge, Neel Krishnan, and Michal Lementowski for invaluable research assistance. The views expressed here are those of the authors and not necessarily those of the Federal Reserve Bank of New York or the Federal Reserve System.

# 1. Introduction

Over the past several years, trading in the U.S. Treasury securities market has migrated from voice-assisted brokers to fully electronic platforms (Mizrach and Neely (2006)). For the most recently auctioned securities in particular, the transition has been nearly complete, with nearly all interdealer trading now taking place via one of two electronic communications networks, BrokerTec and eSpeed (Barclay, Hendershott, and Kotz (2006)). Mizrach and Neely (2006) estimate that BrokerTec accounts for 61% of trading activity in on-the-run securities and eSpeed 39%.

This paper assesses the microstructure of the U.S. Treasury securities market using newly available tick data from BrokerTec. It is the first paper to closely study a U.S. Treasury market electronic communications network (ECN) and one of the first to analyze any fixed income market ECN.[1] Many previous papers have examined the microstructure of the Treasury market using data from GovPX, which consolidates data from voice-assisted brokers.[2] The migration of bond trading to the electronic platforms (which do not contribute to GovPX) has sharply reduced GovPX coverage of the interdealer market, as noted by Boni and Leach (2002), Fleming (2003), and Mizrach and Neely (2006).

Using data from January 2001 to February 2006, we characterize trading activity and liquidity on the BrokerTec platform for the on-the-run 2-, 3-, 5-, 10-, and 30-year Treasury securities. The breadth of the BrokerTec tick data allows us to describe Treasury market depth beyond the inside tier for the first time.

We also calculate the price impact of trades using Escribano and Pascual's (2006) generalization of Hasbrouck's (1991) structural model. While previous studies have assessed price impact using GovPX data (e.g. Fleming (2003), Brandt and Kavajecz (2004), Cohen and Shin (2004), and Green (2004)), the BrokerTec data allow us to consider the price impact of order book information not previously available for the Treasury market.

This paper builds upon earlier studies in the equity market that incorporate order book information into the market impact function. Engle and Patton (2004) were the first to specify individual processes for the bid and ask. Mizrach (2008) added market depth and

[1] Campbell and Hendry (2007) examine price discovery in the 10-year note using transactions data from BrokerTec. Mizrach and Neely (2006) estimate bid-ask spreads and market impact using transactions data from eSpeed. Additional studies examine the euro area sovereign debt market using data from MTS (e.g., Cheung, de Jong and Rindi (2005), Menkveld, Cheung, and deJong (2005), and Beber, Brandt, and Kavajecz (2009)).

[2] Fleming (1997) characterizes intraday liquidity, Fleming and Remolona (1997, 1999), Balduzzi, Elton and Green (2001), Huang, Cai, and Wang (2002), and Fleming and Piazzesi (2005) look at announcement effects, Fleming (2002) examines the relationship between issue size and liquidity, Fleming (2003), Brandt and Kavajecz (2004), Cohen and Shin (2004), Green (2004), and Pasquariello and Vega (2007) assess the information content of trades, Goldreich, Hanke, and Nath (2005) gauge the relationship between liquidity and value, and Brandt, Kavajecz, and Underwood (2007), Campbell and Hendry (2007), and Mizrach and Neely (2008) compare the information content of trades in spot and futures markets.

participant identities in modeling the Nasdaq. We are the first to extend this analysis to the Treasury market.

The ability to enter "iceberg" orders (hidden orders) on the BrokerTec platform also allows analyses not heretofore possible for Treasury securities.[3] We characterize the use of iceberg orders in general and over the trading day. We also test the theoretical implications of Moinas' (2006) model. Moreover, we augment our price impact analysis by considering the effects of hidden depth on price discovery.

Our findings suggest a level of liquidity on the BrokerTec platform markedly greater than that found by earlier studies using data from GovPX. As of early 2006, daily trading volume in the 2-year note averaged about $30 billion. Inside bid-ask spreads for the note average about 1/100th of one percent. An average of over $200 million is available on the platform at the best bid and offer, with even greater amounts available at the adjacent price tiers.

The price impact of trades, quite small to begin with, is even smaller when order book information is taken into account. Baseline estimates find that it takes about $68 million in signed trading volume to move the ask price of the 2-year note 1/256th of one percent of par. However, the baseline estimates appear to be about 11% too large, on average, because they ignore order book information. Moreover, order book changes by themselves seem to have significant effects on prices.

We reexamine our findings about market impact around the release of the Federal Reserve's Federal Open Market Committee decisions. These are one of the most important releases of public information to the market and have significant short term effects on the Treasury limit order book (Fleming and Piazessi (2005)). We find that market impact increases by nearly 50% on average around such announcements and that traders are more reluctant to provide liquidity around such announcements.

We find that iceberg orders are used sparingly in the Treasury market relative to other markets, so that hidden bid depth as a percent of total bid depth averages about 3.3% for the 2-year note. There is considerable variation in the use of iceberg orders, however, so that hidden depth is sometimes quite large. We find that the quantity of hidden depth increases with price volatility, as predicted by theory. Moreover, we find that hidden depth shocks affect prices.

The paper proceeds as follows. Section 2 describes the structure of the interdealer Treasury market. Section 3 describes the BrokerTec data, characterizing trading activity and liquidity in the market. Section 4 develops a structural VAR model and estimates price impact, and in Section 5 we add order book information to the baseline VAR. Section 6 presents theory and empirical evidence on hidden depth. Section 7 concludes.

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[3] Hidden orders in equity markets are examined by Harris (1996), Aitken, Berkman, and Mak (2001), Hasbrouck and Saar (2002), Anand and Weaver (2004), Pardo and Pascual (2006), Tuttle (2006), De Winne and D'Hondt (2007), and De Winne and D'Hondt (2009).

# 2. Market Structure

The secondary market for U.S. Treasury securities is a multiple dealer, over-the-counter market. Trading takes place 22-23 hours per day during the week, although 95% of trading occurs during New York hours, roughly 07:30 to 17:00 Eastern time (Fleming (1997)). The predominant market makers are 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.

Until 1999, nearly all trading in the IDB market for U.S. Treasury securities 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.

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. Cantor spun eSpeed off in a December 1999 public offering. After many ownership changes, eSpeed has now merged with BGC Partners, an offshoot of the original Cantor Fitzgerald.

In June 2000, BrokerTec Global LLC, a rival electronic trading platform, began operations. 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. Mizrach and Neely (2006) describe the migration to electronic trading in greater detail, and Mizrach Neely (2009) provide a summary of the evolution of the microstructure in the Treasury market.

## (a) The Electronic Platforms

BrokerTec and eSpeed are fully automated electronic trading platforms where buyers are matched to sellers without human intervention. The brokers provide electronic screens which display the best bid and offer prices and associated quantities. On eSpeed, for example, a trader can see five price tiers and total size for each tier on each side of the book, plus individual order sizes for the best bid and offer. Traders enter limit orders or hit existing orders electronically. As with the voice brokers, the electronic brokers ensure trader anonymity, even after a trade, and charge a small fee for their services.

The electronic brokers have retained the expandable limit order protocol of the voice-assisted brokers. As explained by Boni and Leach (2004), a Treasury market trader whose order has been executed has the right-of-refusal to trade additional volume at the same price.  In addition to such "workups," both systems allow traders to enter iceberg orders, whereby a trader can choose to show only part of the amount he is willing to trade.  There is an incentive to display quantity, however, or at least enter it as hidden, because shown quantity takes priority over hidden quantity, and hidden quantity at a given price is executed against before a workup starts.

### (b) GovPX

Most previous research on the microstructure of the Treasury market has used data from voice-assisted brokers, as reported by GovPX, Inc.  GovPX receives market information from IDBs and re-disseminates the information in real time via the internet and data vendors.  Information 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.  Over time, the number of brokers declined due to mergers, and a new non-contributing electronic broker (BrokerTec) was formed.  By the end of 2004, GovPX was receiving data from three voice-assisted brokers, but neither eSpeed nor BrokerTec, even though nearly all trading of on-the-run securities had migrated to these fully electronic brokers.  After ICAP's purchase of GovPX in January 2005, ICAP's voice brokerage unit was the only brokerage entity reporting through GovPX.

## 3. Data

Our analysis is based on newly available tick data from BrokerTec for the January 2, 2001 to February 3, 2006 period.  The database provides a comprehensive record of every trade and order book change over the BrokerTec system for the on-the-run 2-, 3-, 5-, and 10-year Treasury notes as well as the 30-year Treasury bond.  The trade data include price, quantity, and whether a trade was seller-initiated (a "hit") or buyer-initiated (a "take").  The order book data specify the price, quantity change, shown and total quantities for that order, whether the order is a bid or an ask, and the reason for the change.  Trades and order book changes are time-stamped to the millisecond.

The order book data provide a view of the Treasury market far more detailed than that provided by GovPX data.  We use the order book changes to recreate the order book on a tick-by-tick basis, saving as much of the richness of the data as is practical.  In particular, our processed dataset not only tells us the best bid and offer and associated sizes at any given time, but also the depth available outside of the first tier.  Moreover, we see the number of individual orders comprising the quantities available at particular prices.  In addition, we are able to discern what quantities were visible to market participants at the time and what quantities were hidden.

Over our sample of 1,269 trading days, BrokerTec intermediated almost $54 trillion in trading of on-the-run coupon securities, or $42.5 billion per day. The activity involved over 11 million trades, or almost 9,000 per day. Moreover, there were over 400 million order book changes on BrokerTec for these securities over our sample, amounting to over 315,000 per day.

## (a) Trends in Trading Activity

Table 1 reports average daily trading frequency and average daily trading volume on BrokerTec by year for our five on-the-run Treasury issues. Trading activity over BrokerTec dwarfs earlier figures based on GovPX data. For example, the average daily number of trades over BrokerTec in early 2006 for the on-the-run 2-year note is 3,656, whereas Fleming (2003) reports a comparable GovPX figure of 483 (based on data from January 1997 through March 2000). Similarly, daily trading volume over BrokerTec for the 2-year note in early 2006 averaged $30.5 billion, versus a GovPX figure from Fleming of $6.8 billion.

[Table 1 – Trading Activity]

Another notable feature of Table 1 is the sharp increase in trading activity on BrokerTec over time. This is also shown by Figure 1, which plots average daily trading volume by month for the five issues. For the 10-year note, for example, the average daily number of trades was 541 in 2001, but 10,335 in early 2006. Similarly, daily trading volume averaged $2.9 billion in 2001, but $27.1 billion in early 2006. The increased trading activity over time is attributable to an overall increase in interdealer trading as well as to an increase in the share of interdealer trading covered by BrokerTec.

[Figure 1 – Monthly Trading Volume]

Because of the trend growth, the remainder of the paper analyzes just the last 13 months of our sample, from January 3, 2005 to February 3, 2006.

## (b) Liquidity around the Clock

Figure 2 plots average BrokerTec trading volume by half hour interval over the round-the-clock trading day for our five instruments. The findings are very consistent with what Fleming (1997) finds using GovPX data from 1994. Trading activity is extremely low during Tokyo trading hours (roughly 18:30 or 19:30 to 03:00 Eastern time), then picks up somewhat during morning trading hours in London. Trading then rises sharply during morning trading hours in New York, peaking between 08:30 and 09:00, and then peaking locally between 10:00 and 10:30. Trading reaches a final local peak between 14:30 and 15:00 and then tapers off by 17:30. This pattern is probably largely explained by scheduled macroeconomic announcements (most of which are made at 08:30 and 10:00), the hours of open outcry Treasury futures trading (08:20 to 15:00), and the pricing of fixed income indices at 15:00.

[Figure 2 – Round-the-Clock Trading Activity]

We are most interested in trading activity during New York trading hours when the vast majority of trading occurs. Therefore, the remainder of the paper generally focuses on market activity between 07:00 and 17:30.

## (c) Pricing Conventions

Tick sizes on the BrokerTec platform vary by security. Treasury notes and bonds are quoted in 32nds of a point, where a point equals one percent of par, but the 32nds themselves can be split into halves and, for some securities, quarters. For the 2-, 3-, and 5-year notes, the tick size is ¼ of a 32nd (or 1/128th) of a point (or 0.0078125% of par). For the 10-year note and 30-year bond, the tick size is ½ of a 32nd (or 1/64th) of a point (or 0.015625% of par).

In the BrokerTec database, prices are reported in 256ths of a point. In the 2-year note, for example, at 09:44:16.339 on June 14, 2005, the bid on BrokerTec was 25508/256 and the ask was 25510/256. We maintain the use of these units throughout our analysis. Note that the tick size for the 2-, 3-, and 5-year notes is 2/256ths and the tick size for the 10-year note and 30-year bond is 4/256ths.

## (d) Inside Spreads and Depth

The most basic measure of the bid-ask spread is the *quoted spread*. The inside quoted spread, $s_t$, is defined as the gap between lowest ask price, $p_t^a$, and the highest bid price, $p_t^b$,

$$s_t = (p_t^a - p_t^b). \tag{1}$$

The second column of Table 2 shows the average inside spread in 256ths. The average BrokerTec spread for the 2-year note is quite close to the spread reported by earlier studies using GovPX data, but the other spreads are narrower. Fleming (2003), for example, reports average bid-ask spreads of 0.21 32nds (1.68 256ths) for the 2-year note and 0.39 32nds (3.12 256ths) for the 5-year note, whereas the corresponding BrokerTec spreads are 2.00 256ths for both securities.[4]

[Table 2 – Inside Bid-Ask Spreads and Depth]

An interesting feature of the BrokerTec spreads is that they are quite close to the minimum tick size for all of the notes (but not the 30-year bond), suggesting that the minimum tick increment may be constraining. Figure 3 shows frequency distributions of inside spreads for the five securities. The figure shows that 90% of inside spreads for the

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[4] Note that the prices in both databases do not reflect brokerage fees. Such fees are proprietary, and can vary by customer and with volume, but are unquestionably lower for the electronic brokers than the voice-assisted brokers.

2-year note are 2/256ths with the remainder roughly split between 0/256ths and 4/256ths. Zero spreads, or “locked” markets, are possible, because prices exclude the brokerage fee, which is commonly higher for the trade aggressor, and because passive limit orders at the same price are not automatically executed against one another.

[Figure 3 – Frequency Distribution of Inside Spread]

Table 2 also shows information on average depth at the inside spread. Average visible depth for each security, shown in the third and fourth columns, greatly exceeds average depths on GovPX reported by earlier studies. For the 2-year note, for example, average bid and ask depth both exceed $200 million, whereas Fleming (2003) reports average depth on GovPX for the note of $25 million (averaging across the bid and ask side).

Table 2 also reports information on the average number of orders accounting for the quantity depth in the fifth and sixth columns. For the 2-year note, for example, an average of nearly 24 orders make up the depth available at both the best bid and the best ask. Comparable data is not available from GovPX. However, even if one assumed that every GovPX order were for the minimum quantity increment of $1 million, the average number of orders would still not match BrokerTec. For the 10-year note, for example, Fleming (2003) reports average depth on GovPX of just under $8 million, whereas we find an average of 15 orders with total depth of almost $50 million on BrokerTec.

In addition to information on visible depth, Table 2 also reports information on hidden depth in the last four columns. Hidden depth is only a small share of total depth, on average. On the bid side, hidden depth as a share of total depth averages 3.3%, 2.5%, 2.0%, 2.0%, and 1.7% for the 2-, 3-, 5-, 10-, and 30-year securities. The corresponding figures on the ask side are uniformly lower, at 2.6%, 1.7%, 1.6%, 1.7%, and 1.3%. Not surprisingly, the number of orders with hidden depth at the inside spread is also relatively low, with an average of just 0.1 orders with hidden depth on each side for the 2-year note.

The low averages mask the fact that there is usually no hidden depth, but when there is hidden depth it is substantial. The shares of order book snapshots with any hidden depth at the first tier on the bid side are thus 11.5%, 5.4%, 4.7%, 5.5%, and 3.0% for the 2-, 3-, 5-, 10-, and 30-year securities. Corresponding figures for the ask side are 8.5%, 3.6%, 3.6%, 4.8%, and 2.2%.

[Figure 4 – Hidden Order Proportions Histogram]

When there is hidden bid depth, its share of total bid depth averages 28.4%, 45.8%, 43.5%, 36.1%, and 58.4% for the five securities. Conditional hidden ask depth proportions are 30.3%, 47.8%, 44.7%, 35.8%, and 59.6%. Figure 4 shows the distribution of hidden depth proportions on the bid side for the first tier, conditional on hidden depth being nonzero.

### (e) Depth away from the Inside Tier

To learn more about depth in the book away from the inside tier, we display a depth histogram of the order book in Figure 5, distinguishing between visible and hidden depth. The figure shows that order book depth outside the first tier is considerable. For the 2-year note, for example, an average of $425 million is available at the second best bid, $349 million at the third best, and $236 million at the fourth best. Given a tick size of 1/128th for the 2-year note, the findings imply a total bid side depth of $1.26 billion within 1/32nd of the best bid (excluding depth available exactly 1/32nd away from the inside bid).

[Figure 5 – Market Depth Distribution]

Another notable feature of the depth distribution patterns is that there is consistently more quantity available at the second and third price tiers than the first. The available quantity peaks at the second tier on both the bid and ask sides for all of the notes, and at the third tier for the bond. Depth then declines monotonically as one moves further away from the inside quotes. For the bond, however, depth at the fifth tier is still higher than depth at the first tier. Biais, Hillion, and Spatt (1995) also find depth lower at the first tier than the second tier, but find similar depths at the second through fifth tiers.

One other interesting finding is that the pattern of hidden depth differs somewhat from that of visible depth. In particular, hidden depth is greatest at the first tier on both the bid and ask sides for the 2- and 3-year notes and 30-year bond. It is greatest at the second tier on both sides for the 5- and 10-year notes. In percentage terms, it is highest at the inside tier for all except the ask side of the 5-year note and the bid side of the 10-year note.

## 4. Baseline Market Impact

We now move beyond the static estimates of price elasticities implied by order book averages. We measure price impact dynamically because order flow may be correlated. Either the subdivision of large orders into smaller trades or positive feedback trading can generate serial correlation in order flow. This is particularly true in an ECN like BrokerTec where large trades hit numerous limit orders in the book.[5]

### (a) Hasbrouck VAR

We begin the estimation of market impact using the standard approach in the literature, Hasbrouck's (1991) vector autoregressive (VAR) model. In Hasbrouck's framework, returns are measured by the quote midpoint,

[5] In our sample, the average first order autocorrelation coefficient on signed order flow is 0.32, ranging from 0.43 for the 2-year note to 0.13 for the 30-year bond.

$$r_t = (p_t^a + p_t^b)/2 - (p_{t-1}^a + p_{t-1}^b)/2 \ . \tag{2}$$

Trades are typically measured only by the direction of trade initiation $x_t$, with a buy order signed +1 and a sell order signed -1. Trade initiation is included in the BrokerTec data set, so all trades are classified properly.

Hasbrouck's identifying assumption is that the current trade affects the current return, but not vice versa,

$$\begin{bmatrix} 1 & -\alpha_{1,2} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} r_t \\ x_t \end{bmatrix} = \beta(L) \begin{bmatrix} r_{t-1} \\ x_{t-1} \end{bmatrix} + \begin{bmatrix} u_{r,t} \\ u_{x,t} \end{bmatrix}. \tag{3}$$

The $\beta(L)$ are $(2\times 2)$ vectors of autoregression coefficients. We estimate (3) using ordinary least squares, using the 4 lags favored by the Akaike Information Criterion, and then compute the impulse response function to a unitary buy shock, $\partial r_{t+s} / \partial u_{x,t}$. The impulse response function is summarized in the first column of Table 3. We look at a 50 quote tick horizon, a period in which the price response stabilizes.

[Table 3 – Hasbrouck Market Impact Estimates]

The price impacts generally rise with maturity, ranging from 0.2375/256th for the 2-year note to 2.0768 for the 30-year bond. The 3-year note has lower trading volume than any other note, and its market impact of 0.4182/256th is higher than that of the 5-year note.

In hybrid markets like the equity market, trades may often be recorded out of sequence, and trade sizes may be adjusted exogenously. In an ECN like BrokerTec, we can be sure that trades are recorded in the proper order and that trade sizes reflect the standing limit orders. For these reasons, we repeat the Hasbrouck VAR using trade volumes, $V_t$.

We now estimate

$$\begin{bmatrix} 1 & -\alpha_{1,2} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} r_t \\ x_t V_t \end{bmatrix} = \beta(L) \begin{bmatrix} r_{t-1} \\ x_{t-1} V_{t-1} \end{bmatrix} + \begin{bmatrix} u_{r,t} \\ u_{xv,t} \end{bmatrix}, \tag{4}$$

using ordinary least squares and the same identification assumption as in (3) and four lags as before.

The market impact estimates from the impulse response function of (4) are found in the second column of Table 3. They are substantially smaller than we found previously, even once you adjust the estimates from (3) for the average trade size. This seems to support adding other liquidity variables like depth into the market impact function.

Market impacts now rise uniformly with maturity, ranging from 0.0108/256th for the 2-year note to 0.6305/256th for the 30-year bond. These estimates imply that a $92 million trade in the 2-year note is needed to move the quote midpoint 1/256$^{th}$, while only $1.59 million is required for the less liquid 30-year bond.

## (b) A Structural Dynamic Model of the Bid and Ask

Recent econometric modeling of the order book by Engle and Patton (2004) has stimulated interest in models which allow for a possibly asymmetric price impact on the bid and ask. Saar (2001), for example, motivates theoretically an asymmetric response for buyer and seller initiated block trades.

We follow Escribano and Pascual's (2006) generalization of Hasbrouck's (1991) structural model. The model allows bid and ask prices to follow separate stochastic processes, but imposes a vector error correction mechanism through the spread. Signed order flow drives the model.

The fundamental value $m_t$ is assumed to follow a random walk apart from shocks to order flow $v_{x,t}$,

$$m_t = m_{t-1} + \lambda v_{x,t} + v_{m,t}. \tag{5}$$

Both bid and ask prices are assumed to deviate only temporarily from fundamental value

$$p_t^b = m_t + \alpha_m^b (m_{t-1} - p_{t-1}^b) + A^b(L)x_t + \alpha_{EC}^b s_{t-1} + v_{pb,t}, \tag{6}$$

$$p_t^a = m_t + \alpha_m^a (p_{t-1}^a - m_{t-1}) + A^a(L)x_t + \alpha_{EC}^a s_{t-1} + v_{pa,t}, \tag{7}$$

Order flow is given by

$$x_t = \mu^a (p_{t-1}^a - m_{t-1}) + \mu^b (m_{t-1} - p_{t-1}^b) + \pi s_{t-1} + v_{x,t}, \tag{8}$$

We interact the trade initiation variable with volume to identify buy and sell shocks distinctly,

$$x_t^b = I(x_t > 0)V_t \tag{9}$$

$$x_t^a = I(x_t < 0)V_t \tag{10}$$

This more flexible specification of the order book allows us to explore asymmetries in market impact.

## (c) Structural VAR

Escribano and Pascual (2006) derive a structural vector error correction representation from models (5)-(10),

$$\begin{bmatrix} 1 & 0 & -\alpha_{1,3} & -\alpha_{1,4} \\ 0 & 1 & -\alpha_{2,3} & -\alpha_{2,4} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \Delta p_t^b \\ \Delta p_t^a \\ x_t^b \\ x_t^a \end{bmatrix} = \gamma(L) s_{t-1} + \beta(L) \begin{bmatrix} \Delta p_{t-1}^b \\ \Delta p_{t-1}^a \\ x_{t-1}^b \\ x_{t-1}^a \end{bmatrix} + \begin{bmatrix} u_{pb,t} \\ u_{pa,t} \\ u_{xb,t} \\ u_{xa,t} \end{bmatrix}, \tag{11}$$

where $\gamma(L)$ is a $(4\times1)$ vector of error correction coefficients, and the $\beta(L)$ are $(4\times4)$ vectors of autoregression coefficients. Using the Akaike information criterion, we again truncate the lag polynomials at 4. The data also support a more parsimonious specification of the AR structure in which bid (ask) prices depend only upon lagged bid (ask) prices, and buys (sells) depend only upon changes in the ask (bid),

$$\begin{bmatrix} 1 & 0 & -\alpha_{1,3} & -\alpha_{1,4} \\ 0 & 1 & -\alpha_{2,3} & -\alpha_{2,4} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \Delta p_t^b \\ \Delta p_t^a \\ x_t^b \\ x_t^a \end{bmatrix} = \gamma(L) s_{t-1} + \begin{bmatrix} \beta_{1,1}(L) & 0 & \beta_{1,3}(L) & \beta_{1,4}(L) \\ 0 & \beta_{2,2}(L) & \beta_{2,3}(L) & \beta_{2,4}(L) \\ 0 & \beta_{3,2}(L) & \beta_{3,3}(L) & \beta_{3,4}(L) \\ \beta_{4,1}(L) & 0 & \beta_{4,3}(L) & \beta_{4,4}(L) \end{bmatrix} \begin{bmatrix} \Delta p_{t-1}^b \\ \Delta p_{t-1}^a \\ x_{t-1}^b \\ x_{t-1}^a \end{bmatrix} + \begin{bmatrix} u_{pb,t} \\ u_{pa,t} \\ u_{xb,t} \\ u_{xa,t} \end{bmatrix}, \tag{12}$$

## (d) Baseline Structural VAR Market Impact

We analyze the impulse response function of (12) at a 50 trade horizon, a period over which the price response stabilizes. Table 4 reports summary effects for our five instruments and Figure 6 illustrates the impulse responses. The price impacts are monotonic in maturity length and show the market to be quite liquid. The estimates range from 0.0147 256ths for the effects of a $1 million buyer-initiated trade on the 2-year note bid price to -1.1125 256ths for the effects of a $1 million seller-initiated trade on the 30-year bond ask price.

[Table 4 – Baseline Structural VAR Market Impact Estimates]

[Figure 6 – Baseline Market Impact Cumulative Impulse Responses]

The estimates imply that a $67 million buyer-initiated trade raises the bid price of the 2-year note 1/256th, while for the less liquid 30-year bond, an $889 thousand seller-initiated trade lowers the ask price by 1/256th.

## (e) Asymmetries

The structural model allows two possible asymmetries. A buy or sell trade may move the bid more or less than the ask, changing the pre-trade bid ask spread,

$$\partial p^b_{t+s} / \partial u_{xb,t} \neq \partial p^a_{t+s} / \partial u_{xb,t}, \;\; \partial p^b_{t+s} / \partial u_{xa,t} \neq \partial p^a_{t+s} / \partial u_{xa,t}. \tag{13}$$

A buy trade could have a proportionally larger or smaller effect than a sell trade of equal size,

$$\partial p^b_{t+s} / \partial u_{xb,t} \neq \partial p^b_{t+s} / \partial u_{xa,t}, \;\; \partial p^a_{t+s} / \partial u_{xa,t} \neq \partial p^a_{t+s} / \partial u_{xa,t}. \tag{14}$$

The only notable asymmetry affecting the spread is in the most illiquid instrument, the 30-year bond. A buy shock widens the bid-ask spread by 0.2775 256ths as buyers do not return as eagerly, even after 50 trade ticks. The spread actually narrows after a sell shock, because the ask falls nearly twice as much as the bid.

A sell shock moves the ask price of the 30-year bond down about 17% more than a buy shock moves it up. Buy shocks and sell shocks have nearly the same impact on the bid though.

We later explore whether these asymmetries widen when the market comes under stress around FOMC announcements.

# 5. Order Book VAR

We now extend our specification to incorporate information from the order book. The decision to place a trade and its size are clearly influenced by the depth in the book. Mizrach (2008) shows that excluding this information is likely to overstate the market impact.

We take our baseline vector error correction model (12) and add the visible inside bid and ask quantity depths, $q^b_t, q^a_t$.[6]

$$\begin{bmatrix} 1 & 0 & -\alpha_{1,3} & -\alpha_{1,4} & 0 & 0 \\ 0 & 1 & -\alpha_{2,3} & -\alpha_{2,4} & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \Delta p^b_t \\ \Delta p^a_t \\ x^b_t \\ x^a_t \\ q^b_t \\ q^a_t \end{bmatrix} = \gamma(L) s_{t-1} + \beta(L) \begin{bmatrix} \Delta p^b_{t-1} \\ \Delta p^a_{t-1} \\ x^b_{t-1} \\ x^a_{t-1} \\ q^b_{t-1} \\ q^a_{t-1} \end{bmatrix} + \begin{bmatrix} u_{pb,t} \\ u_{pa,t} \\ u_{xb,t} \\ u_{xa,t} \\ u_{qb,t} \\ u_{qa,t} \end{bmatrix}, \tag{15}$$

Our vector error correction coefficient $\gamma(L)$ is now $(6\times1)$ and the autoregressive coefficients $\beta(L)$ are $(6\times6)$, before imposing identification assumptions analogous to

[6] We also considered a model that incorporates the number of orders rather than depth, but the results are quite similar to those from (15).

(12),

$$\beta(L)=\begin{bmatrix}\beta_{1,1}(L) & 0 & \beta_{1,3}(L) & \beta_{1,4}(L) & \beta_{1,5}(L) & \beta_{1,6}(L)\\ 0 & \beta_{2,2}(L) & \beta_{2,3}(L) & \beta_{2,4}(L) & \beta_{2,5}(L) & \beta_{2,6}(L)\\ 0 & \beta_{3,2}(L) & \beta_{3,3}(L) & \beta_{3,4}(L) & \beta_{3,5}(L) & \beta_{3,6}(L)\\ \beta_{4,1}(L) & 0 & \beta_{4,3}(L) & \beta_{4,4}(L) & \beta_{4,5}(L) & \beta_{4,6}(L)\\ \beta_{5,1}(L) & 0 & \beta_{5,3}(L) & \beta_{5,4}(L) & \beta_{5,5}(L) & \beta_{5,6}(L)\\ 0 & \beta_{6,2}(L) & \beta_{6,3}(L) & \beta_{6,4}(L) & \beta_{6,5}(L) & \beta_{6,6}(L)\end{bmatrix}. \tag{16}$$

## (a) Implications for Market Impact

The dynamic responses of the bid and ask prices to trades under model (15) are summarized in Table 5.

[Table 5 – Order Book Structural VAR Market Impact Estimates]

The results show that including information on order book depth affects market impact estimates. In particular, the results of (15) suggest that (12) overstates the price impact of trades by an average of 10.8%. For buyer-initiated trades, the overestimate ranges from less than 0.28% for the 30-year bond to 17.4% for the 5-year note. The reductions on the seller-initiated trades are a bit larger, an average 14.9% lower for sell trades on the ask. The reduction in market impact is particularly large for the 2-year note, 24.4%.

## (b) Effects of Order Book Shocks

Theoretical analyses of order books indicate that quotes convey information independent of trades, and we should expect that the arrival of liquidity should have market impact.

We now analyze the dynamic responses of the bid price to changes in displayed depth,

$$\partial p_{t+s}^{b} / \partial u_{qb,t}, \partial p_{t+s}^{b} / \partial u_{qa,t}. \tag{17}$$

These estimates are summarized in Table 6.

[Table 6 – Order Book Impacts]

Adding liquidity to the order book has a much smaller impact on the displayed price quote than a trade. The 0.00015 coefficient on the 2-year note ask, the smallest in the table, implies that a displayed bid liquidity of more than \$6.5 billion is required to raise the ask by 1/256th. In the less liquid 30-year bond, an increase of \$160 million raises the offer by 1/256th.

## (c) FOMC Announcements

In addition to our unconditional analysis, we assess the effects of trade and order book shocks around FOMC announcements. FOMC announcements are key information events for the formation of Treasury prices, precipitating high price volatility, high trading volume, and wide bid-ask spreads (Fleming and Piazzesi (2005)). Green (2004) shows that the information content of trades increases following economic announcements. All of the FOMC announcements in our sample are released at around 14:15; we focus on the 30-minute intervals after these announcements, comparing 14:15-14:45 on announcement and non-announcement days.

We report model (15) estimates of the price impact of trades around FOMC announcements in Table 7. Panel 1 looks at the non-FOMC days, and Panel 2 the nine announcement days. We then plot the dynamic responses in Figure 7. Around FOMC announcements, the market impact of a buyer-initiated trade on the bid price averages 49.9% larger than in the same time interval on non-FOMC days. The increase ranges from 17.7% for the 2-year note to 81.8% for the 30-year bond.

[Table 7 – Market Impact Estimates after FOMC Announcements]

[Figure 7 – Market Impact after FOMC Announcements]

The market impact of seller-initiated trades increases (in absolute value) even more than buy trades after FOMC announcements. A seller-initiated trade has on average a 67.2% larger (absolute) impact on the ask price and a 80.4% larger impact on the bid. The increases in market impact range from 29.2% for the ask-price of the 10-year note to over 100% for the bid and ask impact of the 30-year bond, and the bid impact of the 3-year note. Even controlling for the lack of depth, individual trades appear to work their way through a greater portion of the order book after FOMC announcements.

# 6. Hidden Orders: Theory and Empirics

We now turn to the question of hidden liquidity. While hidden liquidity is a feature of many ECNs, including BrokerTec, very few models of limit order books include the possibility of hidden quantities. One notable exception is the model of Moinas (2006). We use a streamlined version of Moinas' model to derive implications for our empirical analysis.

## (a) Model

The bond price is assumed to have a fundamental value $v$ and, with equal probability, a shock arrives which perturbs the value by $\varepsilon$, $v_H = v + \sigma$, $v_L = v - \sigma$. Without loss of generality, we assume for model development that a positive shock arrives, and that new quotes arrive on the bid.

With probability $\pi_I$, a limit order trader receives valuable private information about the security. The trader improves the inside quote by a tick to $p_t^b$, and his strategic choice is over depth. The trader divides his liquidity between hidden and visible depth,

$$q_t^b = q_t^{v,b} + q_t^{h,b} \tag{18}$$

For simplicity, we assume that the trader chooses among three actions: i) with probability $\pi_1^I$, he displays a quantity of 1, all visible; ii) with probability $\pi_2^I$, he displays a depth of 1, with one unit hidden; and iii) with $\pi_3^I$ probability, he displays a depth of 2, with nothing hidden. If the agent is uninformed, which occurs with probability (1- $\pi_I$), these probabilities are $(\pi_1, \pi_2, \pi_3)$. We summarize this information in Table 8.

[Table 8 – Hidden Model Parameters]

The probability that the agent chooses one hidden and one visible is

$$\Pr(q_t^b = 2 \big| q_t^{v,b} = 1) = \frac{\pi_I \pi_2^I + (1-\pi_I)\pi_2}{\pi_I(\pi_2^I + \pi_1^I) + (1-\pi_I)(\pi_2 + \pi_1)} \tag{19}$$

The seller in this example is a strategic market order trader who trades *m* bonds for liquidity reasons. She has a private benefit of $\theta$ per unit from selling. Her trading profit is uncertain because she does not know *v* or her execution price if there is hidden liquidity.

$$\prod(m) = E\left[m(v_H + \theta - p_t^b(m)) \big| q_t^{v,b}(m)\right] \tag{20}$$

The selling price $p_t^b(m)$ becomes state contingent because if hidden depth is zero, the bid price will fall to the next lowest price tier. We will assume the price drop will wipe out any profit for the seller.

Adverse selection enters into the story because the market trader infers something about *v* from the displayed depth,

$$E\left[v \big| q_t^{v,b} = 1\right] = v - \sigma \frac{\pi_I(\pi_1^I + \pi_2^I)}{\pi_I(\pi_1^I + \pi_2^I) + (1-\pi_I)(\pi_1 + \pi_2)}, \tag{21}$$

$$E\left[v \big| q_t^{v,b} = 2\right] = v - \sigma \frac{\pi_I \pi_3^I}{\pi_I \pi_3^I + (1-\pi_I)\pi_3}. \tag{22}$$

The market order trader contrasts the adverse selection risk against the expected positive gains from trade. The following conditions from Moinas' Lemma 3 describe her choices

$$\pi_2^I + \left(\frac{\sigma-\gamma+\Delta}{\sigma-\gamma}\right)\pi_1^I < \frac{\gamma}{\sigma-\gamma}\frac{1-\pi_I}{\pi_I}\left(\pi_2 + \frac{1-\Delta}{\gamma}\pi_1\right), \tag{23}$$

$$\pi_1^I + \pi_2^I > \frac{\gamma}{\sigma-\gamma}\frac{1-\pi_I}{\pi_I}\left(\pi_2 + \pi_1\right), \tag{24}$$

where $\gamma = v_H + \theta - p_t^b(m)$ and $\Delta = v_H - p_t^b(m)$. If (19) holds, then the dominant strategy for the market order trader is to choose *m = 2*. If (20) holds, she should set *m = 0*. If neither holds, she should set *m = 1*.

There is an equilibrium in mixed strategies as long as adverse selection risk is not too high or too low,

$$\pi_I \in \left]\frac{\gamma\pi_3}{\sigma-\gamma+\gamma\pi_3}, \frac{\gamma-\Delta\pi_1}{\sigma-\Delta\pi_1}\right[. \tag{25}$$

If this condition holds, the informed agent submits hidden limits orders with probability

$$\pi_2^* = 1 - \frac{\gamma}{\sigma-\gamma}\frac{1-\pi_I}{\pi_I}\pi_3. \tag{26}$$

The market order trader learns something about the market when she encounters hidden depth. The amount of information she gains, relative to observed depth, is a function of adverse selection. If we assume that $\pi_I \in \left]0, \frac{\gamma-\Delta s}{\sigma-\Delta s}\right[$, it then follows that

$$E\left[v \middle| q_t^{v,b} = 1, q_t^{h,b} = 1\right] \geq E\left[v \middle| q_t^{v,b} = 2\right]. \tag{27}$$

The market order trader will assign a greater value to the fundamental in this case, and will be more likely to submit a larger order in these circumstances.

## (b) Testable Implications

Following Moinas, we obtain from (26) our first two empirical implications.

*H1: Hidden orders are more likely when adverse selection costs are higher* $\partial\pi_2^*/\partial\pi_I > 0$.

We test whether hidden orders are more prevalent outside of normal trading hours.

*H2: Volatility will increase the proportion of hidden orders,* $\partial\pi_2^*/\partial\sigma > 0$.

We test this directly by relating the proportion of hidden orders to realized volatility.

*H3: The market impact of changes in hidden depth will be larger than for changes in visible depth,.*

We test this directly in an extended VAR which includes hidden depth.

## (c) Empirical Analysis of Hidden Orders

Figure 8 shows that there is an intraday pattern of hidden depth proportions. The figure shows the average percent of depth that is hidden at the bid side of the first tier by hour of the trading day. Depth proportions are lowest during New York trading hours, especially 08:00 to 15:00, and particularly low between 08:00 and 11:00.

[Figure 8 – Intraday Pattern of Hidden Order Proportions]

Given the relative frequency of hidden orders outside of New York trading hours, we accept *H1* that adverse selection increases their use.

The theoretical model also predicts that volatility should increase hidden order proportions. We specify the following model for the bid side. Essentially identical results are obtained for the ask side, so we omit these.

$$h_t^b/(h_t^b+q_t^b) = \alpha + \beta_1 h_{t-1}^b/(h_{t-1}^b+q_{t-1}^b) + \beta_2 \sum_{j=1}^{50} \left| r_{t-j} \right| + v_t \tag{28}$$

$h_t$ is hidden depth, $q_t$ is visible depth, and the volatility measure is the 50-tick absolute return of the midquote. Estimates are in Table 9. The estimates for all five instruments confirm *H2,* that volatility increases hidden order proportions.

[Table 9 – Hidden Order Model with Volatility]

We conclude our empirical analysis by analyzing the effect of hidden orders on our market impact estimates.

We add hidden depth $qh_t^b, qh_t^a$ to the structural VAR in our final model (29),

$$\begin{bmatrix} 1 & 0 & -\alpha_{1,3} & -\alpha_{1,4} & 0 & 0 & 0 & 0 \\ 0 & 1 & -\alpha_{2,3} & -\alpha_{2,4} & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \Delta p_t^b \\ \Delta p_t^a \\ x_t^b \\ x_t^a \\ q_t^b \\ q_t^a \\ qh_t^b \\ qh_t^a \end{bmatrix} = \gamma(L) s_{t-1} + \beta(L) \begin{bmatrix} \Delta p_{t-1}^b \\ \Delta p_{t-1}^a \\ x_{t-1}^b \\ x_{t-1}^a \\ q_{t-1}^b \\ q_{t-1}^a \\ qh_{t-1}^b \\ qh_{t-1}^a \end{bmatrix} + \begin{bmatrix} u_{pb,t} \\ u_{pa,t} \\ u_{xb,t} \\ u_{xa,t} \\ u_{qb,t} \\ u_{qa,t} \\ u_{qhb,t} \\ u_{qha,t} \end{bmatrix}. \tag{29}$$

Our vector error correction coefficients $\gamma(L)$ is now a $(8\times1)$ and the autoregressive coefficients $\beta(L)$ are $(8\times8)$. We impose the same restrictions in the left $(6\times2)$ block of $\beta(L)$ as in (8).

We next look at hidden depth shocks, $\partial\Delta p^{b}_{t+s}/\partial u_{qhb,t}$, $\partial\Delta p^{b}_{t+s}/\partial u_{qha,t}$. At first blush, this is not intuitive, but as Moinas' model shows, even the unseen has visible consequences. The effect of a hidden depth shock, reported in Table 10, can be substantial.

[Table 10 – Market Impact Estimates with Hidden Depth]

A one unit increase in hidden bid depth moves the ask 0.00434 256ths in the case of the 10-year note and 0.13229 256ths in the case of the 30-year bond. Increases in hidden ask depth have a smaller impact, barely moving the 10-year, and only reducing the 30-year bid price by -0.07031. The larger impact of the bid side depth changes is consistent with Saar (2001), even though it is not a direct implication of our model.

We contrast our hidden depth market impact estimates, as the model suggests we should, with the market impact estimates of increases in visible depth. The results are inconclusive. Hidden depth shocks sometimes have a larger impact than visible depth shocks, but not always.

# 7. Conclusion

The microstructure of the U.S. Treasury securities market has changed markedly in recent years with trading activity migrating from voice-assisted brokers to fully electronic brokers. We use newly available tick data from one of these platforms, BrokerTec, to reassess market liquidity. We find that the market is notably more liquid than earlier reports based on GovPX data. As of early 2006, for example, daily trading volume in the 2-year note averaged about $30 billion. Inside spreads average about 1/100th of a percent of par with an average of over $200 million available at the best bid and offer.

The price impact of trades on BrokerTec is quite small, and even smaller once order book information is taken into account. Baseline estimates suggest that it takes $68 million in signed trading volume to move the price of the 2-year note by 1/256th of one percent of par. Taking order book information into account reduces the price impact by about 11%, on average, for the on-the-run securities. Moreover, order book information itself is shown to affect prices.

We find that iceberg orders are used sparingly in the Treasury market. Hidden bid depth as a percent of total bid depth averages about 3.3% for the 2-year note. There is considerable variation in the use of iceberg orders, however, so that hidden depth is sometimes quite large. We find that the use of hidden depth increases with price volatility, as predicted by theory. Moreover, we find that hidden depth shocks affect prices.

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**Table 1**
**Trading Activity**

**(a) Trading Frequency**

| | 2Y | 3Y | 5Y | 10Y | 30Y |
|---|---|---|---|---|---|
| **2001** | 478 | | 592 | 541 | 95 |
| **2002** | 1,142 | | 1,590 | 1,397 | 165 |
| **2003** | 1,252 | 435 | 2,408 | 2,040 | 99 |
| **2004** | 1,924 | 895 | 3,924 | 3,937 | 458 |
| **2005** | 2,965 | 1,839 | 6,669 | 7,308 | 1,262 |
| **2006** | 3,656 | 2,704 | 8,552 | 10,335 | 1,706 |

**(b) Trading Volume**

| | 2Y | 3Y | 5Y | 10Y | 30Y |
|---|---|---|---|---|---|
| **2001** | 7,356 | | 4,460 | 2,882 | 300 |
| **2002** | 12,465 | | 7,536 | 5,259 | 432 |
| **2003** | 11,665 | 2,827 | 9,923 | 6,691 | 264 |
| **2004** | 18,286 | 5,032 | 16,240 | 13,203 | 1,069 |
| **2005** | 27,194 | 7,914 | 23,303 | 21,876 | 2,687 |
| **2006** | 30,497 | 12,224 | 25,435 | 27,143 | 2,836 |

Notes: The table reports daily averages of trading frequency and trading volume on BrokerTec by year for the on-the-run Treasury coupon securities. Volume is reported in millions of dollars. The 2006 figures are based on data through February 3.

**Table 2**
**Inside Bid-Ask Spreads and Depth**

| | | Visible | | | | Hidden | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Maturity** | **Spread** | **Bid Depth** | **Ask Depth** | **# Bids** | **# Asks** | **Bid Depth** | **Ask Depth** | **# Bids** | **# Asks** |
| 2-Year | 1.9956 | 231.45 | 219.33 | 23.84 | 23.64 | 10.53 | 8.42 | 0.12 | 0.09 |
| 3-Year | 2.2389 | 59.58 | 59.75 | 14.08 | 14.29 | 3.24 | 1.88 | 0.06 | 0.04 |
| 5-Year | 2.0033 | 47.15 | 47.61 | 12.89 | 13.02 | 1.81 | 1.91 | 0.05 | 0.04 |
| 10-Year | 3.8089 | 47.89 | 47.43 | 15.15 | 15.10 | 1.53 | 1.88 | 0.06 | 0.05 |
| 30-Year | 7.5770 | 5.93 | 5.95 | 3.90 | 3.95 | 0.26 | 0.28 | 0.03 | 0.02 |

Notes: The table reports average inside bid-ask spreads and depth on BrokerTec for the hours 07:00-17:30 from January 3, 2005 to February 3, 2006. Inside spreads are reported in 256ths of one percent of par and depth is reported in millions of dollars.

**Table 3**
**Hasbrouck Market Impact Estimates**

| | $x_t$ | $x_tV_t$ |
|---|---|---|
| 2Y | 0.23750 | 0.01084 |
| 3Y | 0.41818 | 0.02994 |
| 5Y | 0.35522 | 0.04548 |
| 10Y | 0.56954 | 0.09149 |
| 30Y | 2.07676 | 0.63047 |

Notes: The table reports *50*-tick cumulative market impacts in 256ths of one percent of par. Market impacts in the Hasbrouck model are based on the VAR analysis of quote midpoint returns using either signed order flow $x_t$ as in (3) or signed trading volume $x_tV_t$ as in (4). All the models are estimated for the hours of 07:00-17:30 from January 3, 2005 to February 3, 2006.

**Table 4**
**Baseline Structural VAR Market Impact Estimates**

| | Buy Shock | | Sell Shock | |
|---|---|---|---|---|
| | **Bid** | **Ask** | **Bid** | **Ask** |
| 2Y | 0.01472 | 0.01476 | -0.01496 | -0.01502 |
| 3Y | 0.03993 | 0.04087 | -0.04537 | -0.04355 |
| 5Y | 0.05581 | 0.05786 | -0.05885 | -0.05552 |
| 10Y | 0.12631 | 0.12927 | -0.12489 | -0.12628 |
| 30Y | 0.64570 | 0.92319 | -0.62044 | -1.11252 |

Notes: The table reports *50*-tick cumulative market impacts in 256ths of one percent of par. The structural VAR (12) has quote processes for the bid and ask and signed trade volume. All the models are estimated for the hours of 07:00-17:30 from January 3, 2005 to February 3, 2006.

**Table 5**
**Order Book Structural VAR Market Impact Estimates**

| | **Buy Shock** | | **Sell Shock** | |
|---|---|---|---|---|
| | **Bid** | **Ask** | **Bid** | **Ask** |
| 2Y | 0.01308 | 0.01350 | -0.01151 | -0.01136 |
| 3Y | 0.03496 | 0.03887 | -0.03985 | -0.03653 |
| 5Y | 0.04611 | 0.05036 | -0.05085 | -0.04549 |
| 10Y | 0.11284 | 0.12002 | -0.11450 | -0.11007 |
| 30Y | 0.64390 | 0.93709 | -0.61506 | -1.08029 |

Notes: The table reports *50*-tick cumulative market impacts in 256ths of one percent of par. The model (15) extends the structural VAR (12) with visible bid and ask depth. All the models are estimated for the hours of 07:00-17:30 from January 3, 2005 to February 3, 2006.

**Table 6**
**Order Book Impacts**

| | Bid Depth | | Ask Depth | |
|---|---|---|---|---|
| | **Bid** | **Ask** | **Bid** | **Ask** |
| 2Y | 0.00018 | 0.00015 | -0.00107 | -0.00121 |
| 3Y | 0.00265 | 0.00213 | -0.00154 | -0.00198 |
| 5Y | 0.00384 | 0.00263 | -0.00254 | -0.00370 |
| 10Y | 0.00387 | 0.00203 | -0.00296 | -0.00552 |
| 30Y | 0.04156 | 0.00622 | -0.04671 | -0.06394 |

Notes: The table reports *50*-tick cumulative impacts on the bid and ask quotes in 256ths of one percent of par from a one unit change in visible or hidden depth. The model (15) is a structural VAR with quote processes for the bid and ask, signed trade volume, and the visible bid and ask depth. The model is estimated for the hours of 07:00-17:30 from January 3, 2005 to February 3, 2006.

**Table 7**
**Market Impact Estimates after FOMC Announcements**

**Non-FOMC**

| | Buy Shock | | Sell Shock | |
|---|---|---|---|---|
| | **Bid** | **Ask** | **Bid** | **Ask** |
| 2Y | 0.00979 | 0.00988 | -0.00737 | -0.00751 |
| 3Y | 0.02682 | 0.02575 | -0.03746 | -0.03242 |
| 5Y | 0.03408 | 0.04145 | -0.04229 | -0.03825 |
| 10Y | 0.06964 | 0.09311 | -0.09056 | -0.08836 |
| 30Y | 0.59606 | 0.62651 | -0.75024 | -0.74470 |

**FOMC Announcements**

| | Buy Shock | | Sell Shock | |
|---|---|---|---|---|
| | **Bid** | **Ask** | **Bid** | **Ask** |
| 2Y | 0.01152 | 0.01203 | -0.01333 | -0.01190 |
| 3Y | 0.04198 | 0.03980 | -0.08400 | -0.05104 |
| 5Y | 0.05276 | 0.06076 | -0.06678 | -0.06964 |
| 10Y | 0.09639 | 0.10174 | -0.12533 | -0.11418 |
| 30Y | 1.08380 | 1.15137 | -1.50551 | -1.55659 |

Notes: The table reports *50*-tick cumulative market impacts in 256ths of one percent of par. The model (15) is estimated from 14:15-14:45 on non-FOMC and nine FOMC announcement days.

**Table 8**
**Hidden Model Parameters**

| **Strategy** | **Limit Order Size** | | **Probabilities** | |
|---|---|---|---|---|
| | Hidden | Visible | Informed | Uninformed |
| Small unhidden | $q_t^{h,b} = 0$ | $q_t^{v,b} = 1$ | $\pi_1^I$ | $\pi_1$ |
| Large hidden | $q_t^{h,b} = 1$ | $q_t^{v,b} = 1$ | $\pi_2^I$ | $\pi_2$ |
| Large unhidden | $q_t^{h,b} = 0$ | $q_t^{v,b} = 2$ | $\pi_3^I$ | $\pi_3$ |

**Table 9**
**Hidden Order Model with Volatility**

| | Constant | Hidden Depth(-1) | Volatility | $R^2$ |
|---|---|---|---|---|
| 2Y | 0.0928 | 0.8224 | 18.8698 | 0.755 |
| | (122.49) | (479.18) | (4.44) | |
| 3Y | 0.3395 | 0.4851 | 3.3105 | 0.375 |
| | (171.75) | (138.26) | (3.59) | |
| 5Y | 0.1857 | 0.7088 | 2.0374 | 0.640 |
| | (189.65) | (402.03) | (2.74) | |
| 10Y | 0.1343 | 0.7653 | 4.0739 | 0.698 |
| | (173.56) | (487.90) | (2.70) | |
| 30Y | 0.5172 | 0.2855 | 2.3886 | 0.198 |
| | (202.74) | (71.74) | (1.96) | |

Notes: The table reports estimates of (28). The dependent variable is the ratio of hidden bid depth at the first tier to total bid depth at the first tier, and the volatility measure is the 50-period moving average of the absolute return on the inside mid-quote.

**Table 10**
**Market Impact Estimates with Hidden Depth**

**Panel 1: Bid Depth**

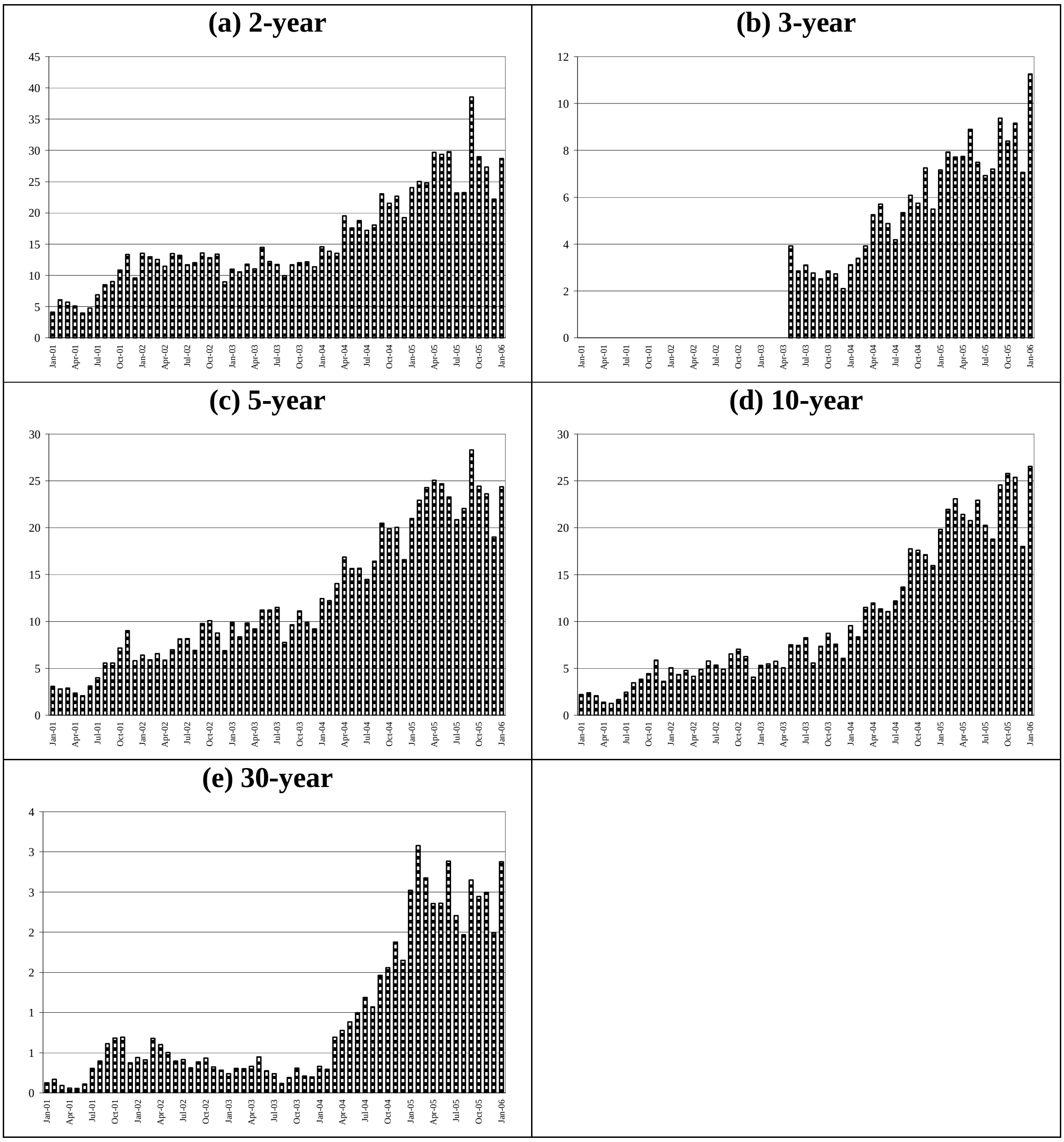
| | Visible Depth | | Hidden Depth | |
|---|---|---|---|---|
| | **Bid** | **Ask** | **Bid** | **Ask** |
| 2Y | 0.00017 | 0.00014 | 0.00071 | 0.00069 |
| 3Y | 0.00263 | 0.00211 | 0.00159 | 0.00132 |
| 5Y | 0.00382 | 0.00261 | 0.00189 | 0.00105 |
| 10Y | 0.00384 | 0.00201 | 0.00643 | 0.00434 |
| 30Y | 0.04184 | 0.00713 | 0.00979 | 0.13229 |

**Panel 2: Ask Depth**

| | Visible Orders | | Hidden Orders | |
|---|---|---|---|---|
| | **Bid** | **Ask** | **Bid** | **Ask** |
| 2Y | -0.00106 | -0.00120 | -0.00022 | -0.00039 |
| 3Y | -0.00155 | -0.00198 | -0.00097 | -0.00122 |
| 5Y | -0.00254 | -0.00370 | -0.00005 | -0.00003 |
| 10Y | -0.00295 | -0.00551 | -0.00001 | -0.00002 |
| 30Y | -0.04683 | -0.06493 | -0.07031 | -0.00456 |

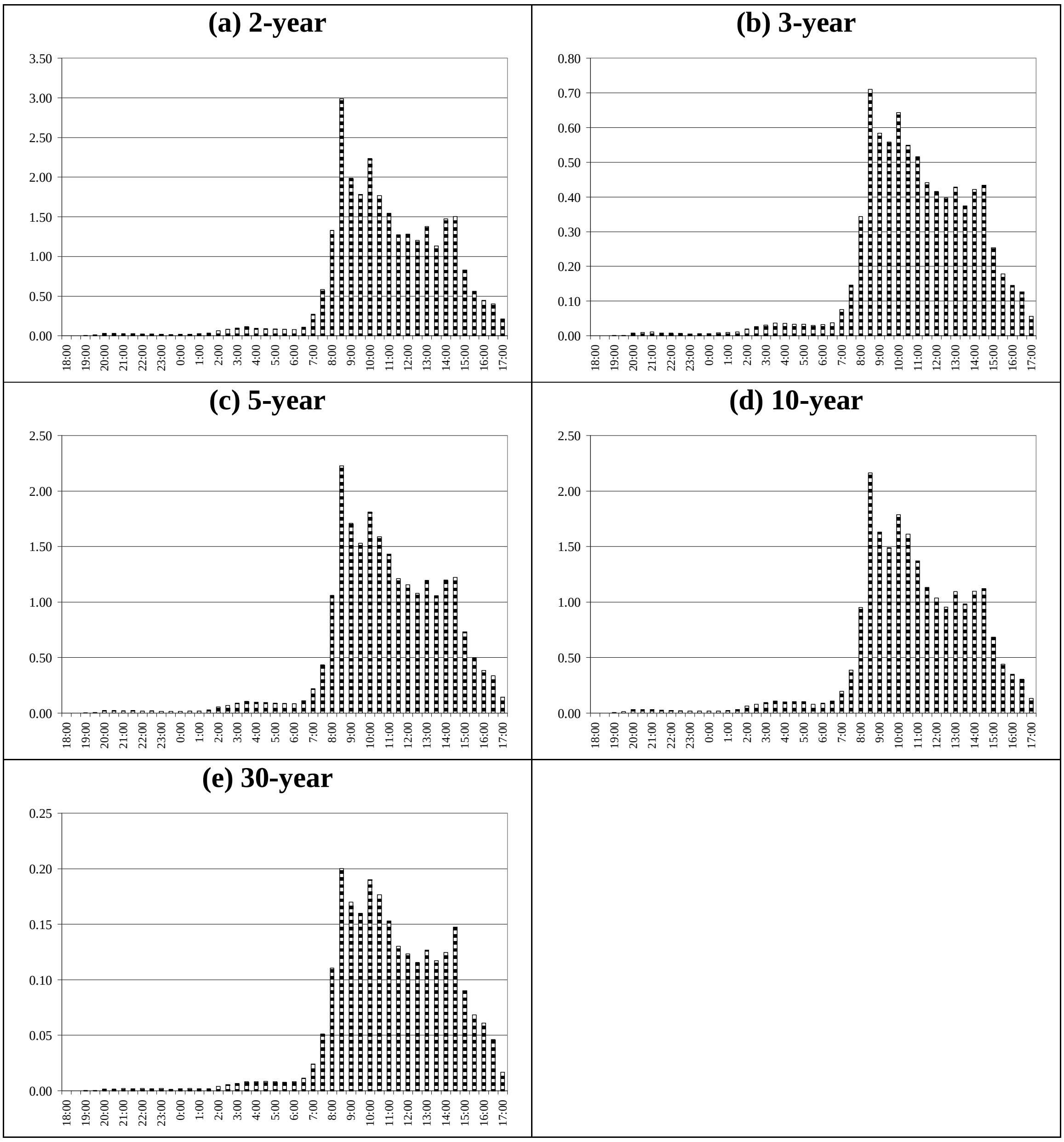
Notes: The table reports *50*-tick cumulative impacts on the bid and ask quotes in 256ths of one percent of par from a one unit change in visible or hidden depth. The model (29) is a structural VAR with quote processes for the bid and ask, signed trade volume, the visible bid and ask depth, and the hidden bid and ask depth. The model is estimated for the hours of 07:00-17:30 from January 3, 2005 to February 3, 2006.

**Figure 1**
**Monthly Trading Volume**



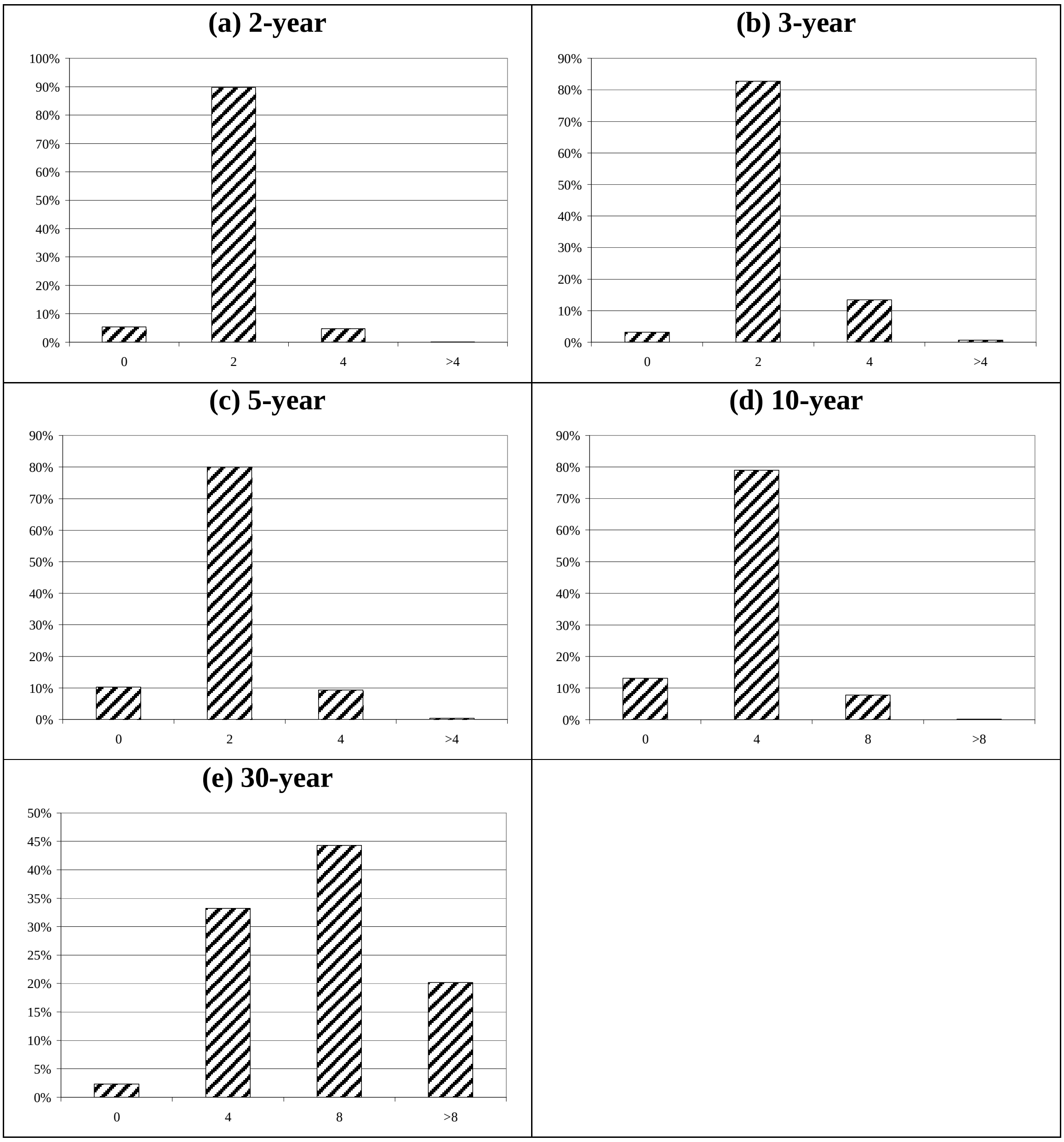

Note: The figures show daily average BrokerTec trading volume by month in billions of dollars from January 2001 to January 2006.

**Figure 2**
**Round-the-Clock Trading Activity**



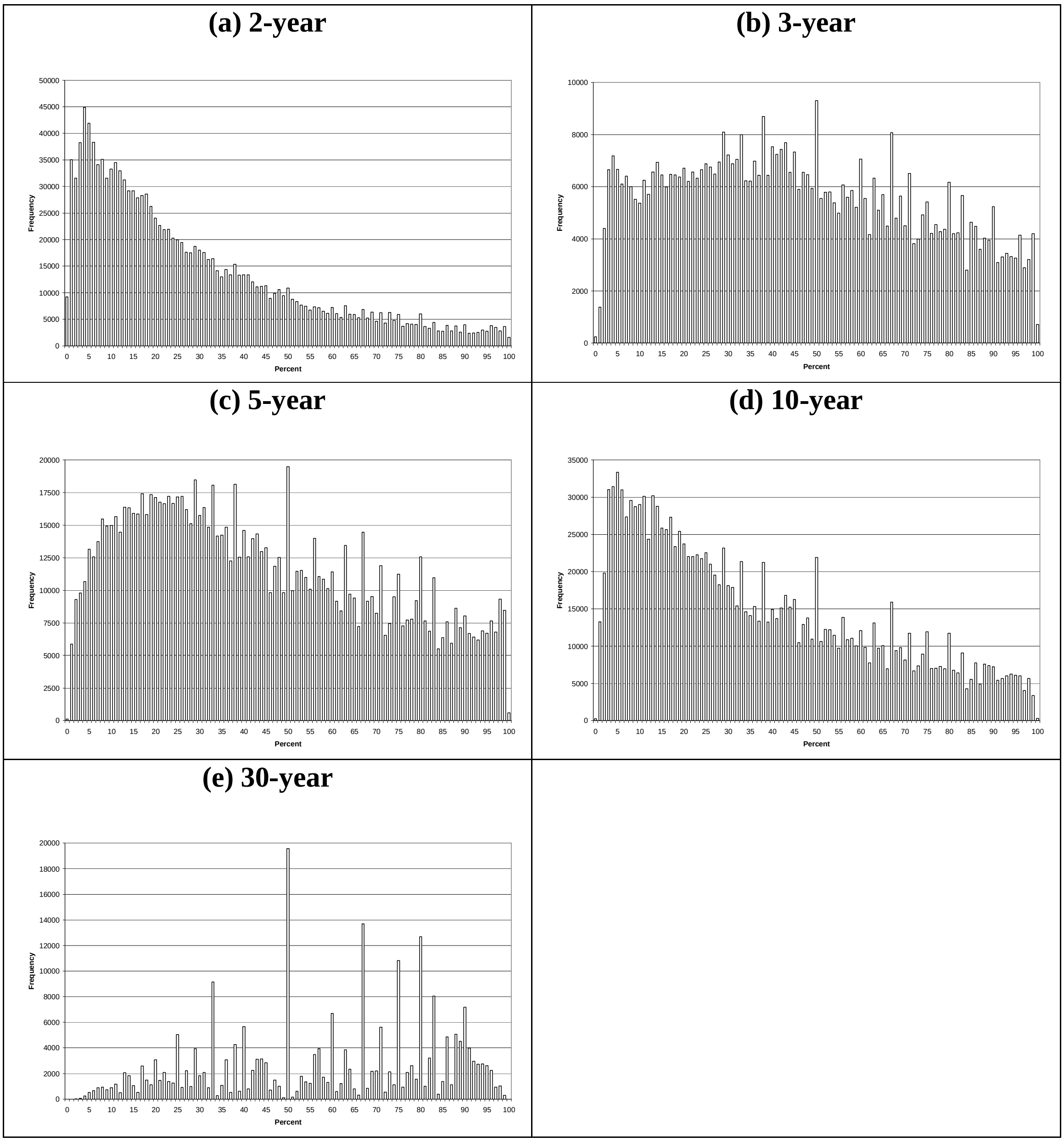

Note: The figures show average BrokerTec trading volume in billions of dollars per half hour interval for the sample period January 3, 2005 to February 3, 2006.

**Figure 3**
**Frequency Distribution of Inside Spread**



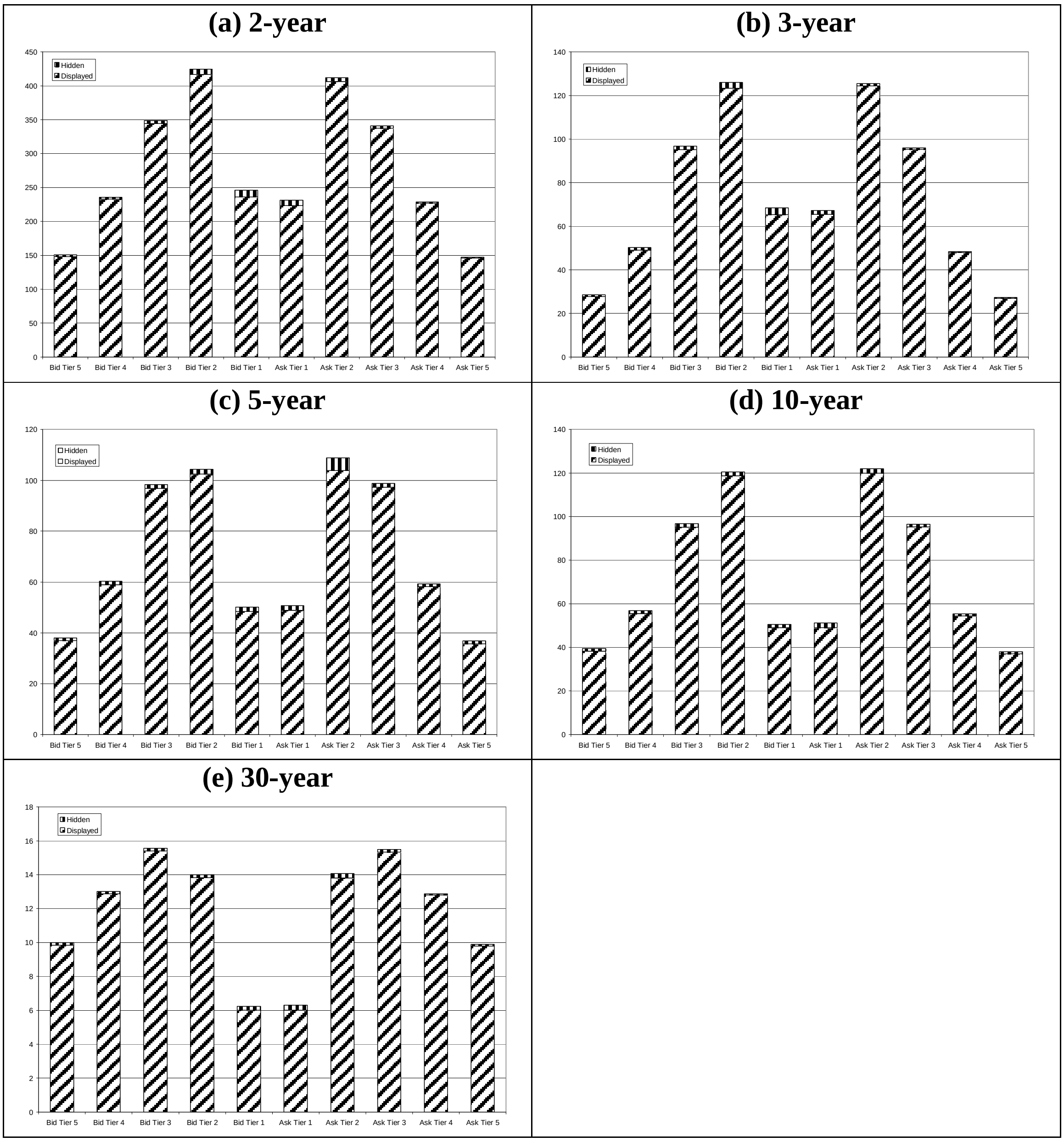

Notes: The figures show the frequency distribution of the inside spread on BrokerTec in 256ths of one percent of par. The time period is 07:00-17:30 and the sample period is January 3, 2005 to February 3, 2006.

**Figure 4**
**Hidden Order Proportions Histogram**



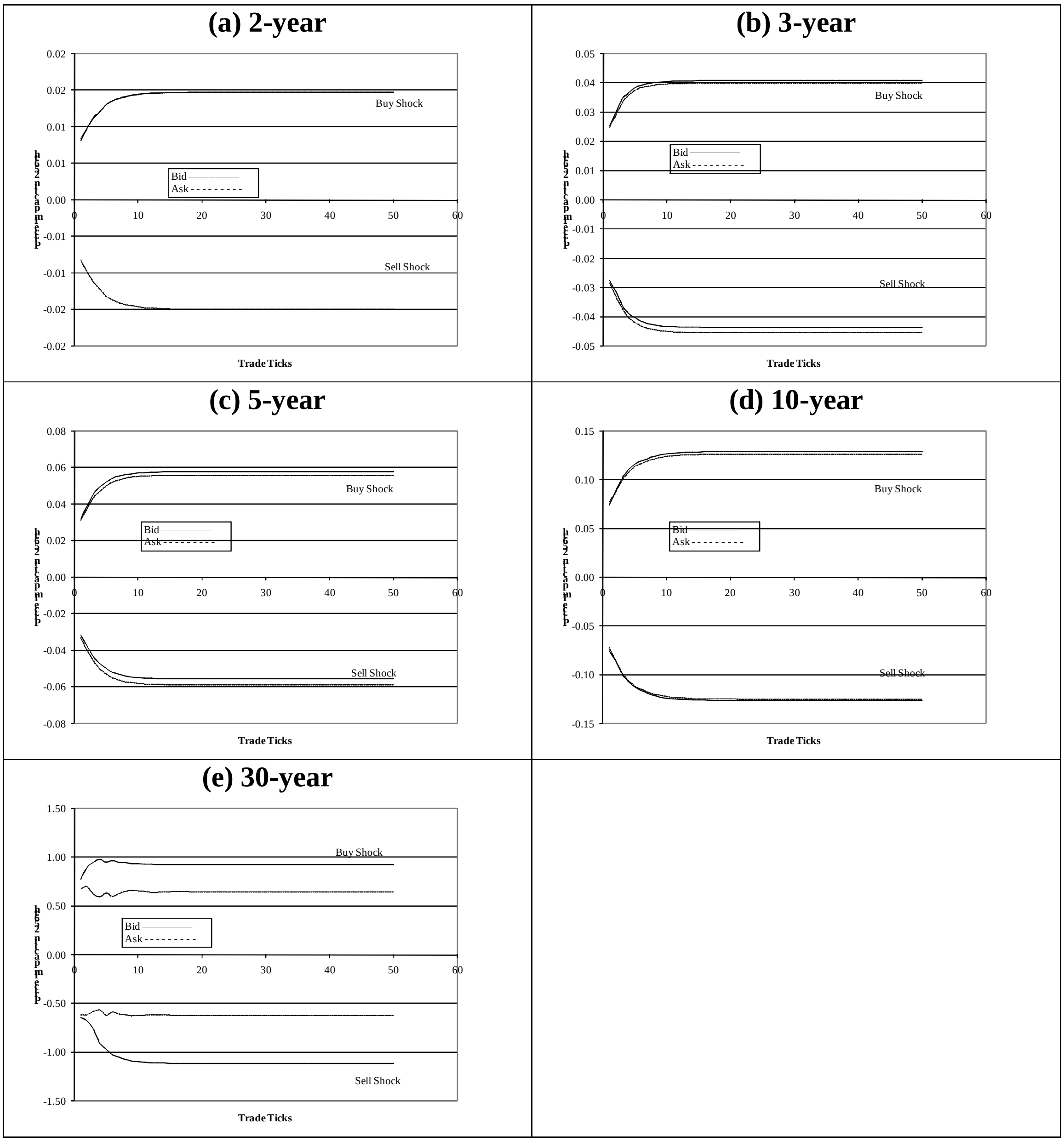

Notes: The figure presents the frequency distribution of hidden bid depth at the first tier as a percent of total bid depth at the first tier conditional on hidden bid depth being nonzero. The sample period is January 3, 2005 to February 3, 2006.

**Figure 5**
**Market Depth Distribution**



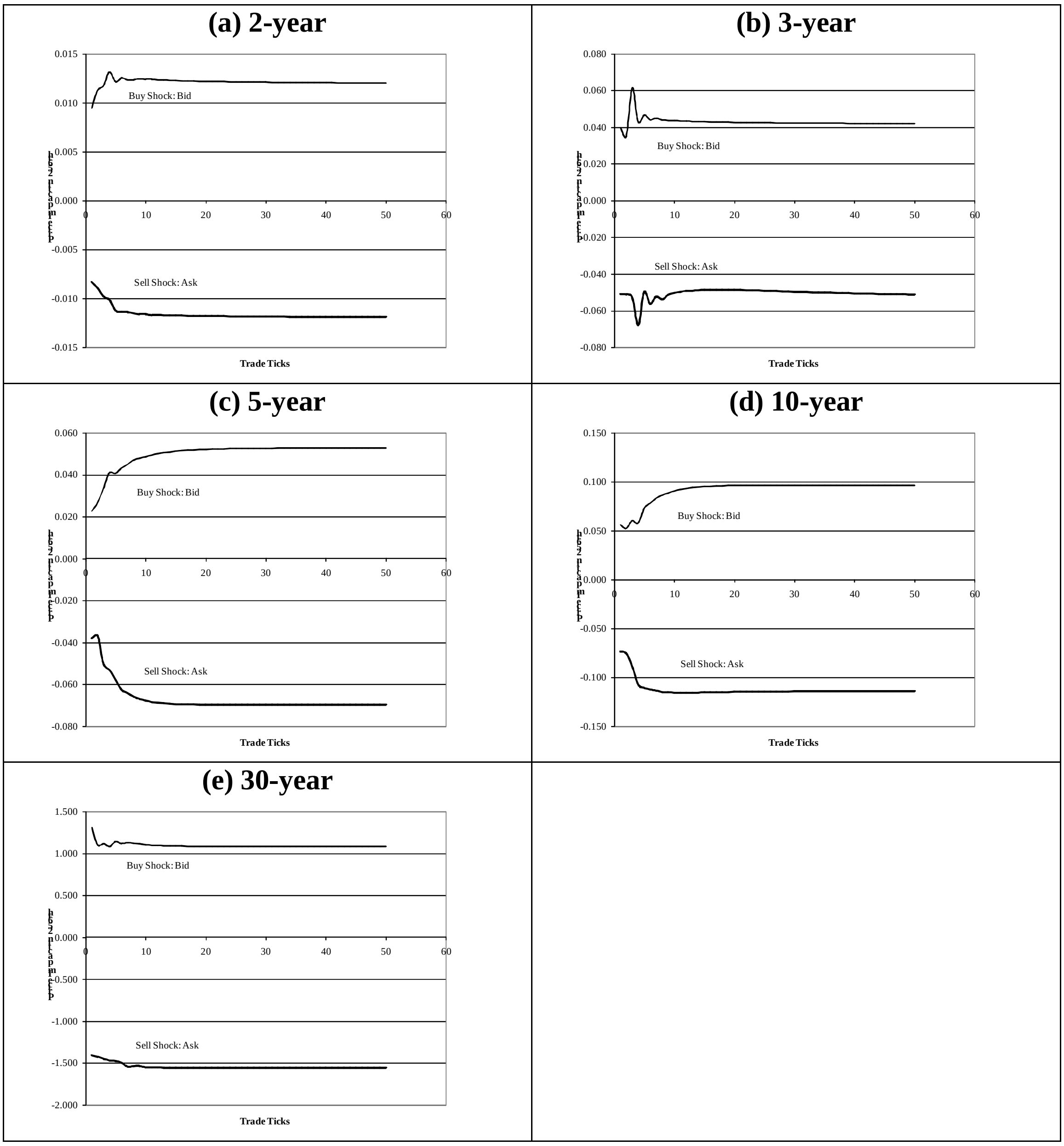

Notes: The figure depicts the frequency distribution of average daily hidden and visible depth by price tier. The time period is 07:00-17:30 and the sample period is January 3, 2005 to February 3, 2006.

**Figure 6**
**Baseline Market Impact Cumulative Impulse Responses**



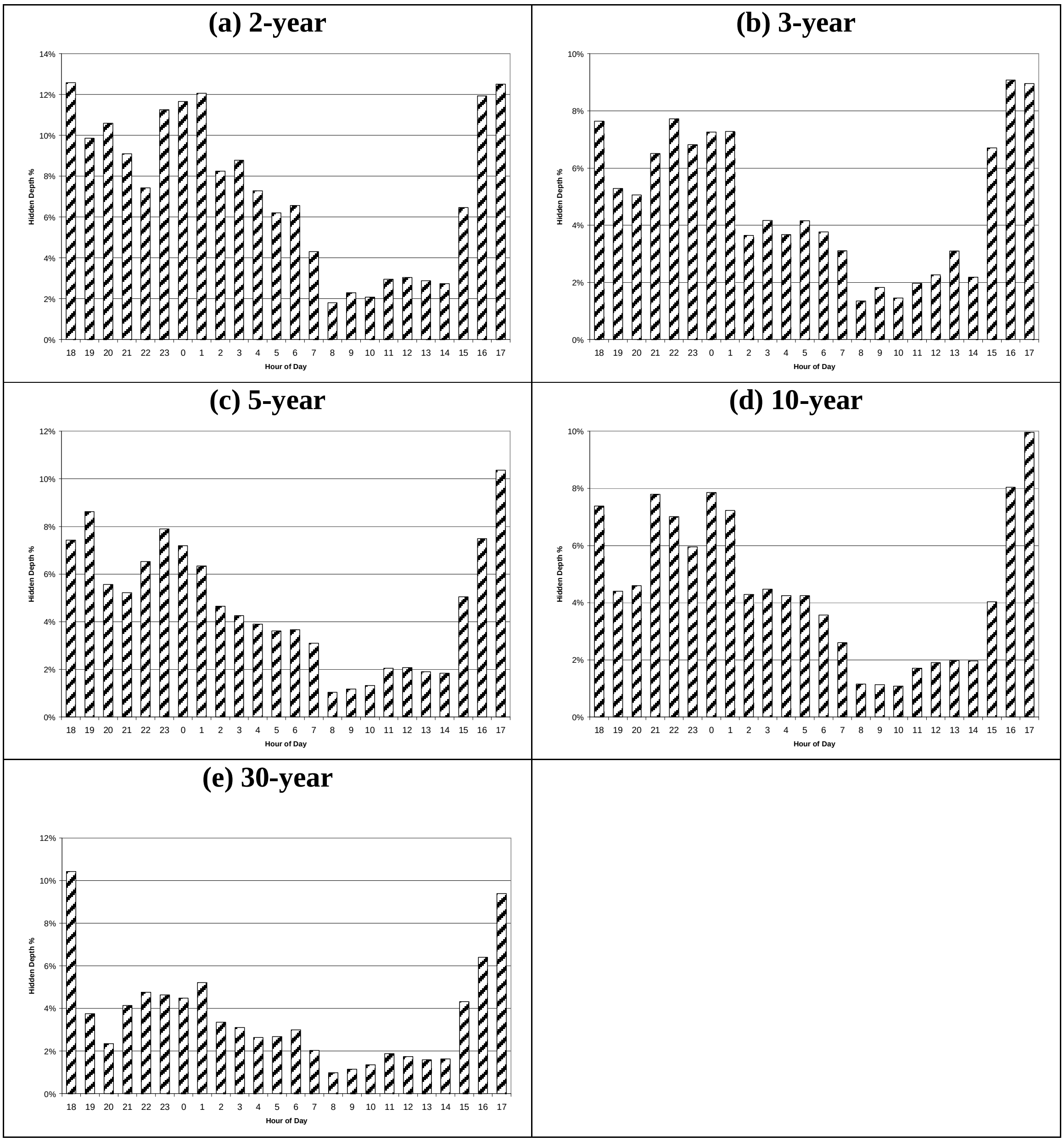

Notes: The figure depicts the market impact in model (12) of $1 million buyer- and seller-initiated trades on the bid and ask in 256ths of one percent of par. The sample period is January 3, 2005 to February 3, 2006.

**Figure 7**
**Market Impact after FOMC Announcements**




Notes: The figure depicts the model (15) market impact of $1 million buyer-initiated trades on the bid and seller-initiated trades on the ask in 256ths of one percent of par. The sample period 14:15-14:45 on the nine FOMC announcement days between January 3, 2005 and February 3, 2006.

**Figure 8**
**Intraday Pattern of Hidden Order Proportions**




Notes: The figure presents hourly averages of hidden bid depth at the first tier as a percent of total bid depth at the first tier. The sample period is January 3, 2005 to February 3, 2006.