PRICE FORMATION AND LIQUIDITY IN THE U.S. TREASURIES MARKET: EVIDENCE FROM INTRADAY PATTERNS AROUND ANNOUNCEMENTS

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Abstract

We find striking intraday adjustment patterns for price volatility, trading volume, and bid-ask spreads in the U.S. Treasuries market around the time of macroeconomic announcements. The patterns suggest certain hypotheses about price formation and liquidity provision in multiple-dealer markets. These hypotheses assign new importance to public information, heterogeneous views, sluggish price discovery, traditional inventory-control behavior by market makers, and liquidity traders who react with a lag to price changes.

Keywords: Price formation, liquidity, intraday patterns, announcements, Treasury securities market

JEL classification code: G14

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Introduction

We identify striking intraday patterns in the behavior of price volatility, trading volume, and bid-ask spreads in the U.S. Treasury securities market around the time of macroeconomic announcements. Using newly available interdealer broker data, we find that the bid-ask spread widens dramatically to anticipate an announcement, commencing a brief period of illiquidity. There is then a notable lack of trading volume at the time of the most volatile prices, which occur in the first two minutes after a major announcement. Trading volume surges only after an appreciable lag. Liquidity returns in the form of a narrowing spread as soon as trading volume surges. High levels of price volatility and trading volume then persist for over an hour, with volume persisting somewhat longer. Such patterns suggest hypotheses about the price formation process and the provision of liquidity in a market where dealers compete as both informed investors and market makers.

Three strands of the empirical literature on how markets process information have together led to the conclusion that private information is the dominant source of price volatility in stock markets. First, the "mixture of

distributions hypothesis" of Clark (1973), Epps and Epps (1976), and Tauchen and Pitts (1983) suggests that prices and volume jointly depend on the arrival of information, public or private. Second, French and Roll (1986) show that stock return volatilities are higher when the exchanges are open than when they are closed. By looking at Wednesdays when the exchanges happened to be closed, they attribute the pattern not to the release of public information during normal business hours but to the effect of private information conveyed through trading. Third, Berry and Howe (1994) develop an intraday measure of public information flow based on Reuter's news releases and find no significant relationship between their measure and stock price volatility.

The provision of liquidity in financial markets is the responsibility of market makers. In the market microstructure literature, recent models of market making based on asymmetric information have challenged the more traditional models based on inventory control. The inventory-control models (e.g., Demsetz, 1968; Tinic and West, 1972; and Ho and Stoll, 1983) emphasize the risks to market makers of high price volatility and low trading volume, resulting in a bid-ask spread that widens with volatility and narrows with volume. The asymmetric-information models (e.g., Glosten and Milgrom, 1985; and Kyle, 1985), however, suggest that if some investors had superior information, the risk to market makers and the spreads they quote would depend on when the informed and uninformed trade. Admati and Pfleiderer (1988), for example, propose that discretionary liquidity traders would cluster their trading activity around certain times of the day and that the resulting liquidity would attract the informed investors who would in turn bring price volatility. Hence high volume, high volatility, and narrow spreads would coincide. The evidence from the stock market tends to favor the asymmetric-information view (e.g., Madhavan and Smidt, 1991; and Hasbrouck, 1991), while evidence from the foreign exchange market supports both views (Lyons, 1995).

In this paper, we study the price formation process and the provision of liquidity in the interdealer cash market for U.S. Treasury securities. The market is dominated by primary dealers who compete both as informed investors and market makers. We focus on the intraday price and trading patterns around the time of major macroeconomic announcements, examining the patterns at both one-minute and five-minute intervals. These scheduled announcements are useful because they identify precise times at which information is released. Ederington and Lee (1993) and others rely on such announcements to explain intraday price volatility in various futures and currency markets.[1] Until now, however, the lack of data on trading volumes and bid-ask spreads has inhibited the discussion about the way markets process information and provide liquidity.

We propose several hypotheses to explain the stylized facts. First, the volatility spike immediately after an announcement implies a dominant role for public information, for which price adjustment requires no trading activity. Second, the ensuing surge in volume arises from wide disagreement among investors regarding the price adjustment. Third, the persistence of high volatility along with high volume represents a price-volume relationship that arises from sluggishness in the formation of a consensus price. Fourth, the brief period of illiquidity around announcements demonstrates the importance of inventory-control factors in market making. Finally, the persistence of high volume beyond the period of high volatility indicates the presence of liquidity traders who react with a lag to price changes.

The paper is organized as follows: In Section I, we characterize the market described by our data. In Section II, we describe the data used in the

[1] Crain and Lee (1995), Andersen and Bollerslev (1996), and Locke (1996) examine announcement effects in precious metals markets and other futures and currency markets.

analysis. In Section III, we examine the basic intraday patterns and distinguish the patterns that can be attributed to the macroeconomic announcements. In Section IV, we identify the announcements that have the most impact on the market. In Section V, we document five stylized facts about the timing and persistence of the announcements' effects on volatility, volume, and the spread. In Section VI, we discuss hypotheses about the price formation process and liquidity provision to explain the stylized facts.

I. The Interdealer Treasury Securities Market[2]

Trading in U.S. Treasury securities takes place primarily in a multiple-dealer over-the-counter market rather than an organized exchange.[3] While there are 1,700 brokers and dealers trading in the secondary market, the majority of trading volume is accounted for by the 37 primary dealers.[4] Primary dealers are those eligible to trade directly with the Federal Reserve Bank of New York.[5] These dealers are expected to bid competitively at the Treasury auctions, participate in the Fed's open market operations, and provide market intelligence to the Fed. Until recently, primary dealers were also required to transact significant volume with customers and thereby maintain a liquid secondary

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[2] Additional sources on the U.S. Treasuries market are Bollenbacher (1988), Department of the Treasury (1992), Fleming (1996), Madigan and Stehm (1994), Stigum (1990), and U.S. General Accounting Office (1986).

[3] While Treasuries are traded on the New York Stock Exchange and the American Stock Exchange, exchange trading is negligible compared to that of the over-the-counter market.

[4] Department of Treasury (1992).

[5] The ranks of primary dealers consist of diversified securities firms, money center banks, and specialized securities firms, and include foreign-owned as well as domestically owned firms. A list of the primary dealers is provided in Appendix A.

market for Treasury securities.[6] While trading with customers is no longer required, primary dealers remain the predominant market makers in U.S. Treasury securities. It is evident that the dealers compete as both market makers and informed investors.

As market makers, the primary dealers take positions and stand ready to buy and sell securities for their own account at their quoted bid and ask prices. The positions taken, in fact, tend to be highly leveraged, as they are typically financed with borrowings in the overnight repo market. The dealers trade 22 to 23 hours per day during the five day trading week, although 95% of trading activity occurs during New York trading hours.[7] Primary dealers trade an average of $125 billion a day in the U.S. Treasuries cash market.[8] Just over half of this volume is with customers and just under half is transacted with other primary dealers. Roughly 90% of the interdealer volume occurs through interdealer brokers.

The interdealer brokers are at the core of the secondary market for U.S. Treasury securities.[9] The brokers provide primary dealers with electronic screens that post the best bids and offers phoned in by the dealers. Dealers execute trades by phone through the brokers, who then also post the resulting trade price and size electronically. For the most part, the brokers act only as

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[6] Customers refer to entities that are not primary dealers or brokers, and in practice include non-primary dealers, other financial institutions (e.g., banks, insurance companies, pension funds, and mutual funds), non-financial institutions, and individuals.

[7] Madigan and Stehm (1994) and Fleming (1996) describe the round-the-clock market. The volume statistics in this paragraph are from Fleming (1996).

[8] In contrast, trading volume on the New York Stock Exchange averages $9.7 billion a day (NYSE *Fact Book for the Year 1994*).

[9] The six major interdealer brokers are: Cantor Fitzgerald Inc., Garban Ltd., Hilliard Farber & Co. Inc., Liberty Brokerage Inc., RMJ Securities Corp., and Tullett & Tokyo Securities Inc.

agent and serve only primary dealers.[10] The interdealer broker market is extremely liquid with *minimum* trade sizes of $1 million ($5 million for bills), bid-ask spreads of less than two hundredths of a point for the most active 5-year note, and modest brokerage fees.[11]

An important feature of the interdealer broker market is the anonymity of trading. The brokers are "blind" in the sense that they do not reveal to the counterparties to a transaction the other's name.[12] Since the market is limited to dealers who are perceived to have been vetted by the Fed, there is little concern that a counterparty might renege on a transaction.[13] The anonymity of trading indicates the importance of individual primary dealers' private information or views. Different dealers are known to have different analytical strengths, investment strategies, and customers, and the same trade by one dealer, if identified, would not convey the same information if undertaken by another dealer.

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[10] Cantor Fitzgerald Inc. is the most notable exception on both points.

[11] Typical brokerage fees (paid by the transaction initiator) are as follows: $12.50 per $1 million on 3-month bills (¼ of a hundredth of a point), $25 per $1 million on 6-month and 1-year bills (½ and ¼ of a hundredth of a point respectively), and $39.06 per $1 million on notes and bonds (1/8 of a 32nd of a point). These are the fees reported by Stigum (1990), and recent communication with market participants suggests that fees today are similar. The fees are negotiable, however, and can vary with volume.

[12] Stigum (1990) explains that clearing trades through a clearing bank allows brokers not to reveal names on trades done through them (p. 436).

[13] Officially, the Fed states, "The designation [of primary dealer] is not an endorsement, is not conferred under regulatory authority, and does not entail official supervision by the Federal Reserve." (Federal Reserve Bank of New York, 1988).

II. Data

Our data cover one year of tick-by-tick trading activity among the primary dealers in the interdealer broker market. The source of the data is GovPX, Inc., a joint venture set up by the primary dealers and interdealer brokers in 1991 to improve the public's access to U.S. Treasury security prices. GovPX consolidates and posts real-time quote and transactions data from 5 of the 6 major interdealer brokers, accounting for two-thirds of the interdealer broker market.[14] Posted data include the best bids and offers, trade prices and sizes, and the aggregate volume of trading for all Treasury bills, notes, and bonds. GovPX data are distributed electronically to the public through several on-line vendors.

The sample period is August 23, 1993 to August 19, 1994, a year in which the Federal Reserve raised its target fed funds rate five times. After excluding 10 days when the market was closed, we have a sample of 250 trading days. We focus our analysis on the *on-the-run* 5-year Treasury note. On-the-run securities (also called *active* or *current*) are the most recently issued securities of a given maturity and account for the majority of interdealer trading volume.[15] Among the on-the-run issues, the 5-year note is the most actively traded security among the brokers reporting to GovPX (Fleming, 1996). During our sample period, GovPX posted a daily average of 2,167 bid-ask quotations and 659 trades for the on-the-run 5-year note. Appendix B describes the cleaning and processing of the data in some detail.

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[14] Cantor Fitzgerald Inc. is not included. Cantor specializes in longer-term securities and in particular the 30-year bond.

[15] Fleming (1996) finds that 64% of interdealer trading is in on-the-run issues, 25% is in *off-the-run* issues, and 12% is in *when-issued* securities. Off-the-run securities are issued securities that are no longer active, while when-issued securities are securities that have been announced for auction but not yet issued.

We also collected data on the date and time of 19 different regularly scheduled macroeconomic announcements. These include 18 monthly announcements that regularly appear in "The Week Ahead" section of *Business Week* as well as one weekly announcement.[16] The federal government's "Schedule of Release Dates" and the *Wall Street Journal* were used in addition to *Business Week* to determine announcement dates and times. As seen in Table I, 11 of our announcements are released at 8:30 AM eastern time (ET), one at 9:15 AM, six at 10:00 AM and one at 2:00 PM.[17] Seventeen of the announcements come from government agencies and two from the private sector. Our period of analysis encompasses 268 of these announcements on 173 separate days.

III. Intraday Patterns

In this section, we describe the basic intraday patterns of price volatility, trading volume, and bid-ask spreads and distinguish the patterns that can be attributed to the scheduled macroeconomic announcements. We examine these patterns specifically for the on-the-run 5-year Treasury note for successive five-minute intervals from 7:30 AM to 5:00 PM (ET). As mentioned before, these trading hours account for nearly 95 percent of interdealer trading, and all of the announcements we examine occur during these hours. To isolate the role of the

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[16] One of these "monthly" announcements is gross domestic product (GDP). While GDP is a quarterly statistic, advance, preliminary, and final estimates are released in successive months. Our list of announcements is the same as Ederington and Lee's (1993) except for the addition of initial jobless claims and consumer confidence, and the omission of installment credit. We exclude installment credit since it does not occur at a fixed time.

[17] Included in the 8:30 A.M. count is personal income, which was released at 10:00 A.M. for the first four announcements.

scheduled announcements, we compare the intraday patterns on announcement days with the patterns on nonannouncement days. An announcement day is one in which one of our 19 scheduled announcements was made, and a nonannouncement day one in which none of the announcements was made.

To examine intraday price volatility we take the change in log prices for each five-minute interval. Here and throughout the paper, prices are defined as the midpoints between bid and ask quotes, and the price changes are calculated with the last set of quotes posted during an interval.[18] We then calculate the standard deviation of these log price changes for each interval across our 250 trading days. We measure trading volume as the total face value of securities traded during each interval and then take the mean across days. We measure the bid-ask spread as the mean difference between bid and ask quotes divided by the mean midpoint between bid and ask quotes for each interval and then take the mean across trading days. In the figures and in our discussion we refer to the different time intervals by the interval starting times, e.g., 8:30 AM for the 8:30-8:35 AM interval.

Price volatility

The most distinctive feature of the average intraday pattern of price volatility is a spike in the 8:30 AM interval. As shown in Figure 1A, volatility rises sharply at that time and remains relatively flat the rest of the day, except for minor spikes at 10:00 AM and 1:45 PM. Ederington and Lee (1993) find similar spikes in the T-bond, Eurodollar, and deutsche mark futures markets, and they attribute the pattern to the effects of a number of scheduled macroeconomic announcements released at those times of the day.[19] Indeed, as shown in Figure

[18] We also have transactions prices but using the bid-ask midpoints allows us to avoid complications associated with the "bid-ask bounce" and provides us with more observations.

[19] Crain and Lee (1995), Andersen and Bollerslev (1996), and Locke (1996) find the same effects in precious metals and other interest rate and currency markets.

1B, volatility on announcement days exhibits a pronounced spike at 8:30 AM and a less pronounced one at 10:00 AM. In our sample, 11 different scheduled announcements are released at 8:30 AM and six at 10:00 AM. By comparison, volatility stays relatively flat through nonannouncement trading days.

Trading volume

Our data provide new evidence on the intraday patterns of trading volume in the U.S. Treasuries market. In this market, average trading volume also surges around 8:30 AM but its subsequent decline is more gradual than the decline in volatility. As shown in Figure 2A, volume is rising from the start of New York trading at 7:30 AM. Trading volume then peaks occurs at 8:35 AM or five minutes after the volatility peak. Except for a minor surge after 10:00 AM, volume declines only gradually until 3:00 PM, when it then falls sharply. The great volume surge around 8:30 AM and the minor surge around 10:00 AM can be attributed to the announcements. As shown in Figure 2B, the surge at 8:35 AM is much more pronounced for announcement days, and the smaller surge around 10:00 AM is clearly evident only for announcement days. For much of the rest of day, volume on announcement days remains higher than volume on nonannouncement days. Announcement and nonannouncement day patterns are similar, however, in that both show a rise in volume before 8:30 AM and a sharp drop after 3:00 PM.[20]

The bid-ask spread

Our data also provide new evidence on the intraday patterns of liquidity in the U.S. Treasuries market as measured by the bid-ask spread. In this market, the average bid-ask spread displays a rough reverse J-shaped pattern interrupted

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[20] The early morning volume surge and the sharp drop in the afternoon may be related to the opening of the futures markets in Chicago at 8:20 AM (ET) and the closing of those markets at 3:00 PM (ET).

by a sharp rise around 8:30 AM and a smaller rise around 10:00 AM.[21] As shown in Figure 3A, the spread is widest at the start of New York trading indicating an initial reluctance by dealers to provide liquidity. The spread then narrows rapidly from 7:30 AM, then widens sharply for a brief period around 8:30 AM. It then narrows again, and widens briefly around 10:00 AM. The spread then rises gradually until the early afternoon, tapers off slightly and then rises sharply just before trading ends. The momentary loss of liquidity around 8:30 AM and 10:00 AM, as indicated by the wide spreads, can be attributed to the announcements. As shown in Figure 3B, the reverse J-shaped pattern is evident on both announcement and nonannouncement days, while the interruptions of wide spreads are evident only for announcement days.

IV. The Most Important Announcements

Earlier announcement studies

Several studies, such as Roley and Troll (1983), Urich and Wachtel (1984), Hardouvelis (1988), and Dwyer and Hafer (1989), use daily return data to examine the impact of monthly economic announcements.[22] These studies typically estimate the effects of the surprise components of the announcements on the level of interest rates. While the producer price index (PPI) is generally found to have an impact in the early studies, most monthly announcements are

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[21] McInish and Wood (1992) observe such a reverse J-shaped pattern for stocks traded on the New York Stock Exchange.

[22] There is also an extensive literature examining the impact of the weekly money supply announcements on interest rates. See Hardouvelis (1984) for references to the earlier literature. More recent papers include Thornton (1989) and Strongin and Tarhan (1990).

found to have no significant effects.[23] More recently, however, Cook and Korn (1991) demonstrate the importance of the employment report on daily returns and document its increasing significance in recent years.

The availability of intraday price data has greatly increased the power of tests that examine announcement effects. Ederington and Lee (1993) examine the impact of monthly economic announcements on the Treasury bond futures, Eurodollar futures, and deutsche mark futures. They find employment, PPI, the consumer price index (CPI), and durable goods orders in that order as having the largest price volatility effects for interest rate futures, with generally similar findings for deutsche mark futures markets. Extensions of this work have considered spot market responses (Crain and Lee, 1995), market expectations regarding the announcements (Becker, Finnerty, and Kopecky, 1996), and other determinants of price volatility (Andersen and Bollerslev, 1996). Locke (1996) finds a surge in trading activity as well as price volatility around announcements in interest rate futures, foreign exchange, and precious metals markets.

Measuring the impact of announcements

We now examine the effects of the various announcements on price volatility, trading volume, and the bid-ask spread in the U.S. Treasuries market. Following Ederington and Lee (1993), we run cross-sectional regressions of volatility, volume, and spread on announcement dummy variables for given five-minute intervals. Specifically, we define dummy variables D_{kn} where D_{kn} =

[23] The PPI is found to have an impact on interest rates in Urich and Wachtel (1984), Hardouvelis (1988), and Dwyer and Hafer (1989), but not Roley and Troll (1983). Roley and Troll (1983) do find evidence in favor of the industrial production index impacting rates, but Hardouvelis (1988) and Dwyer and Hafer (1989) do not. Hardouvelis (1988) finds significant effects for the consumer price index, the trade balance, and the unemployment rate, but none of these other studies that look at these variables find them significant. Hardouvelis (1988) also uncovers evidence that durable goods orders, personal income, and retail sales impact interest rates.

1 if announcement k is made on day n and $D_{kn} = 0$ otherwise.[24] The regression equation is then $Y_{nt}^j = a_{0t}^j + \sum_{k=1}^{K} a_{kt}^j D_{kn} + e_{nt}^j$ where the superscript j indicates whether the dependent variable is volatility, volume, or spread, the subscript t indicates the time interval, and K is the number of different announcements included in the regression. The intercept a_{0t}^j measures the average value of the variable in time interval t in the absence of announcements and the coefficient a_{kt}^j measures the average impact of announcement k. We measure price volatility here as the absolute value of the change in log prices. As before, trading volume is defined as the total face value of securities traded during an interval and the bid-ask spread is defined as the mean bid-ask quote difference divided by the mean midpoint of the bid and ask quotes for an interval.

For each dependent variable we conduct the regression analysis for four different time intervals corresponding to the four times of day that the 19 reports are released. In the case of price volatility and the bid-ask spread these regressions are run for the five-minute intervals immediately following the announcements (e.g., 8:30-8:35 AM for the 8:30 AM announcements). In the case of trading volume these regressions are run for the succeeding five-minute interval (e.g., 8:35-8:40 AM for the 8:30 AM announcements). The patterns displayed in Charts 1B, 2B, and 3B suggest that these are the intervals in which the announcements have their most pronounced effects on the corresponding variables.

The number of announcements K included in each set of regressions varies. Specifically, we include dummy variables for those announcements

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[24] In our sample, two announcements -- construction spending and the NAPM survey -- were released on the same day in 10 of 12 instances. In those 10 cases, we set the dummy variable equal to one; and for the days with only one of these announcements, we set it equal to one-half.

released at *or before* the corresponding interval time. The 9:15 AM set of regressions, for example, includes dummy variables for both the 8:30 AM and 9:15 AM announcements, but not the 10:00 AM or 2:00 PM announcements.[25] This procedure controls for the effects that earlier announcements might have on subsequent volatility, volume, or spreads that day. To save space and focus on the important findings we do not present the control-variable results.

Our regression results in Table II therefore measure the immediate impact of the various announcements on price volatility, trading volume, and the bid-ask spread. As shown in the table, nine of the 19 announcements show significant effects on price volatility at the 1% level and none at the 5% level. Six of the announcements show significant effects on trading volume at the 1% level and five at the 5% level. Ten show significant effects on the bid-ask spread at the 1% level and four at the 5% level.

The most important announcements

To compare announcements released at different times of the day, we calculate the ratio of the coefficient a_{kt}^{j} to the intercept a_{0t}^{j}. The announcements with the greatest effects on price volatility, which are also significant at the 1% level, in the order of their importance are: employment, PPI, construction spending and the NAPM survey, CPI, gross domestic product (GDP), retail sales, industrial production and capacity utilization, consumer confidence, and new single-family home sales. For trading volume, the most important announcements are: employment, construction spending and the NAPM survey, PPI, new single-family home sales, retail sales, and industrial production and capacity utilization in that order. For the bid-ask spread, the most important

[25] Personal income was released at 10:00 AM for the first four announcements in our sample and at 8:30 AM thereafter. When it is an 8:30 announcement we include it in the regressions for intervals at and after 8:30. When it is a 10:00 announcement we include it only for intervals at and after 10:00.

announcements are: employment, CPI, new single-family home sales, PPI, GDP, durable goods, industrial production and capacity utilization, construction spending and the NAPM survey, consumer confidence, and initial jobless claims in that order.

One of our striking findings is the high correlation across variables in which announcements seem to matter.[26] For price volatility, trading volume, and the bid-ask spread the 8:30 AM employment report is far and away the most important announcement.[27] In the first five minutes upon the report's release, volatility rises 13-fold on average and the spread widens to three times its usual value. Then in the next five-minute interval, volume surges to three-and-a-half times its normal amount. While the rank ordering of announcements varies somewhat after employment, there is nonetheless a strong relationship across variables in which announcements matter. The PPI, for example, is ranked second for impact on price volatility, third for trading volume, and fourth for the bid-ask spread.

This section has identified the immediate impact of the various announcements on volatility, volume, and the spread. We next turn to the adjustment of the market to announcements over somewhat longer time periods. To conduct clearer tests, we focus on the major 8:30 AM announcements, which we define as those that show significant effects on at least two of the variables at the 1% level. By this criterion, the major 8:30 AM announcements are employment, PPI, CPI, GDP, and retail sales.

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[26] The correlation between the 19 price volatility and trading volume coefficients in Table II is 0.89, significant at the .01 level. Corresponding figures for the price volatility and bid-ask spread coefficients and the trading volume and bid-ask spread coefficients are 0.80 and 0.91, respectively (both significant at the .01 level).

[27] As noted by Ederington and Lee (1993), the employment report is the first government report released concerning economic activity in a given month.

V. Five Stylized Facts

We use the major 8:30 AM announcements as conditioning variables to clarify the stylized facts about the intraday patterns of price volatility, trading volume, and bid-ask spreads. The precise time for the release of the announcements provides an especially useful reference point for analyzing the timing and persistence of various effects. In the analysis, we look at both one-minute and five-minute intervals. Table III compares days with any of the major 8:30 AM announcements identified in Section IV (employment, PPI, CPI, GDP, or retail sales) with nonannouncement days for each *one-minute* interval from 8:25 to 8:37 AM. Table IV compares the same days for each *five-minute* interval from 8:15 to 8:45 AM and for every third five-minute interval from 9:00 to 10:20 AM. Figures 4A to 4C compare volatility, volume, and spread between announcement and nonannouncement days for the whole trading day, indicating the instances when the differences are significant. These tables and figures serve to document five stylized facts:

Stylized fact 1: Volatility spikes without volume

The most volatile prices occur with a notable lack of trading volume in the first few minutes after a major 8:30 AM announcement. Panel A of Table III reports the standard deviation of changes in log prices over one-minute intervals on announcement days, the standard deviation on nonannouncement days, and the ratio of the standard deviations. Panel B reports mean trading volume on announcement days, the mean on nonannouncement days, and the difference between the two. As shown in Panel A, price volatility starts to rise a minute before an announcement.[28] Volatility then spikes up in the next two minutes,

[28] Ederington and Lee (1995) also note a rise in volatility in anticipation of an announcement.

reaching a peak of over 12 times the volatility for the same interval on nonannouncement days. As shown in Panel B, during these two minutes, trading volume tends to be less than the normal volume on nonannouncement days, although the difference is not statistically significant. This lack of trading volume during the time of the most volatile prices is striking, because to our knowledge it has not been documented in the literature, even by researchers who have analyzed the effects of public announcements.[29] We find that not only is it possible for prices to move with little trading volume but the most dramatic price movements actually take place without a significant rise in trading volume.

Stylized fact 2: Volume surges with a lag

Trading volume does rise after an announcement but only with an appreciable lag. As shown in Panel B of Table III, it takes two minutes for volume to start to pick up after a major announcement, by which time price volatility has already come down to a third of its level at the peak. Volume then surges to its highest levels between four and seven minutes after an announcement, when it averages about four times its average for nonannouncement days. During this volume surge, volatility remains high but at a level that is only a fifth of its peak level.

Stylized fact 3: Both volatility and volume persist at high levels and decline together

Price volatility and trading volume both decline gradually while remaining high for over an hour after a major 8:30 AM announcement. Panels A and B of Table IV compare price volatility and trading volume on announcement and nonannouncement days by *five-minute* intervals. As shown in the table, volatility begins a process of decline after the spike but tends to remain

[29] Locke (1996), for example, examines 15-minute intervals and finds that increased volume accompanies the heightened volatility after announcements.

significantly higher than average for an hour after the announcement. In other words, conditional volatility during the period is serially correlated. Beyond this period, we observe significantly higher volatility for several more intervals but these tend not to be consecutive intervals. Figure 4A shows the ratio of the volatility on major 8:30 AM announcement days to the volatility on nonannouncement days by five-minute intervals, indicating the ratios that are significant at the 1% and 5% levels. Price volatility is significantly higher on announcement days for every interval from 8:30 AM to 9:25 AM. Several intervals of significantly higher volatility occur until early in the afternoon, but after 11:30 AM such intervals are few and far between.

As shown in Table IV, trading volume on announcement days starts to decline by 8:40 AM but remains significantly higher than on nonannouncement days. Figure 4B shows the difference between trading volume on major 8:30 AM announcement days and volume on nonannouncement days by five-minute intervals. Trading volume is significantly higher on announcement days for every interval from 8:30 AM to 10:10 AM. Intervals of significantly higher volume are then fairly common until 1:00 PM. The fact that both volume and volatility remain high for an extended period of time and decline together suggests that their behavior is part of a process set off by the announcements.

Stylized fact 4: The market suffers a momentary liquidity loss at the time of announcements

The market suffers some liquidity loss during a brief period around announcements. An inverse measure of liquidity, the bid-ask spread widens dramatically with a major announcement but narrows as soon as volume surges. Panel C of Table III reports the mean bid-ask spread over one-minute intervals on announcement days, the mean on nonannouncement days, and the difference between the two. As shown in the panel, the spread starts to widen three

minutes before a major announcement while price volatility is still not significantly higher than average. The most illiquid time coincides with the volatility spike in the first minute after the announcement. During this time, the spread is nearly six times wider than its average on nonannouncement days.[30] In the next two minutes, liquidity returns as the spread begins to narrow. Three minutes after the announcement, the spread is no longer significantly different from the nonannouncement day average. During this time, price volatility remains high but trading volume has started to surge. Figure 4C shows the difference between the mean bid-ask spread on major 8:30 AM announcement days and the mean spread on nonannouncement days by five-minute intervals. The figure shows that the spread is wider than the nonannouncement day average for several more intervals after the announcement.

Stylized fact 5: High volume persists longer than high volatility

The announcement effects on trading volume appear to last longer than the effects on price volatility. Table IV and Figure 4A suggest that significantly higher volatility persists for at least an hour and possibly three hours after an announcement. Such effects appear somewhat similar to those Ederington and Lee (1993) found in their data, in which they detect significant effects on volatility for 40 minutes and slight effects for several hours. We find the effects on trading volume to be even more persistent. Table IV and Figure 4B suggest that significantly higher volume persists certainly for an hour-and-a-half and perhaps for four-and-a-half hours. Not only do we find the largest price movements when there is little trading volume, we also find active trading when there is little price movement. In the stock market, Beaver (1968), Morse (1981), and Gallant, Rossi, and Tauchen (1992) also observe that high volume persists after high price volatility has ended.

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[30] In contrast, Krinsky and Lee (1996) find an insignificant effect of earnings announcements on bid-ask spreads for NYSE and AMEX stocks.

The stylized facts in one episode

The stylized facts we described are discernible even when we look at a single episode. The largest volatility shock in our sample, took place just after 8:30 AM on August 5, 1994 when the July employment report was released. Figure 5 shows the spread between the mean bid and ask quotes, the mean transactions price, and trading volume by one-minute intervals from 8:00 AM to 10:00 AM on that day. As shown in the figure, in the half hour before the announcement, the price of the 5-year note was relatively stable, the bid-ask spread narrow, and trading volume low. The bid-ask spread then started to widen a minute before the announcement. Upon the report's release, the price of the 5-year note fell about 50 hundredths of a point within three minutes of the announcement, with trading still relatively thin. The spread, which was at its widest in the first two minutes after the announcement, narrowed quickly in the third minute as trading volume started to pick up. Volume then surged as the price continued to fluctuate. For the next hour-and-a-half, both price volatility and trading volume remained substantially higher than on nonannouncement days.

VI. Some Hypotheses

We propose five specific hypotheses to explain the stylized facts. These hypotheses assign important roles to public information, heterogeneity of investors' views, sluggishness in price formation, inventory control behavior by market makers, and liquidity traders who react with a lag to price changes. These roles have not been emphasized in the recent empirical literature, but we argue that they offer a consistent explanation of the price formation process and the provision of liquidity in the U.S. Treasuries market.

Hypothesis 1: Public information plays a dominant role in bond price adjustment

The fact that the most volatile prices occur with relatively little trading volume suggests a dominant role for public information. French and Roll (1986, p. 9) distinguish between public information, "which affects prices before anyone can trade on it," and private information, which "only affects prices through trading." This dichotomy neatly identifies public information as the factor driving the large price movements we find in the first few minutes after an announcement. This result is reassuring, because the announcements *should* contain largely public information. During these moments, the bid-ask spread is at its widest, and this may explain the reluctance to trade.[31] During this period, there is also no evidence of a price-volume relationship. Table V reports the contemporaneous correlations between price volatility and trading volume across days for one-minute intervals between 8:25 and 8:49AM. There is a notable absence of a significant positive correlation between volatility and volume in the first two minutes after an announcement, in contrast to the significantly positive correlations in most of the other intervals.

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[31] Since volatility, volume, and spread are endogenous, it is also partly true that the spread is wide because of low volume and high volatility.

The initial price adjustment after an announcement is a measure of the amount of public information contained in the announcement. We find that price changes in the first five minutes after a major 8:30 AM announcement explain nearly half of price changes between 7:30 AM and 5:00 PM on those days.[32] The regressions reported in Table II measure this initial price adjustment for the different announcements. The estimates suggest that the employment report contains the most public information, followed by PPI, construction spending and the NAPM survey, CPI, and GDP.

The dominant role we assign to public information in the bond market stands in sharp contrast to its humble role in the stock market. French and Roll's ingenious study of stock return volatility around Wednesdays when the New York and American stock exchanges were closed to remedy a processing backlog suggests that the high volatility during exchange trading hours is explained by private rather than public information. Stoll and Whaley (1990) also conclude that private information is the dominant factor in stock return volatility. Berry and Howe (1994) develop an intraday measure of public information flow based on Reuter's news releases and find no significant relationship between their measure and stock price volatility.[33] In the bond market's case, Ederington and Lee (1993) did point to the announcements as a major source of price volatility, and it would seem obvious that the announcements contain largely public information. However, they lacked the data to show that much of the volatility took place without a rise in trading volume.

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[32] The regression of the daily change in log prices (i.e., from 7:30 AM to 5:00 PM) on the five-minute change results in an adjusted R-squared of 0.470. The adjusted R-squared is a slightly higher 0.506 if absolute price changes are used instead of signed price changes.

[33] The study by Jones, Kaul, and Lipson (1994) is an exception in this literature. They find that the adverse-selection component of bid-ask spreads (a component they associate with private information) on NASDAQ-NMS stocks is small and conclude that public information drives short-term volatility.

Hypothesis 2: The surge in volume arises from wide disagreement about the price

It is remarkable that trading volume surges to its highest levels only after the initial price adjustment following an announcement. Our hypothesis is that the trading activity arises from an initially wide disagreement among investors regarding the price adjustment. The hypothesis harks back to Beaver (1968, p. 69) who attributed the price changes in the stock market in weeks of annual earnings announcements to "changes in the expectations of the market as a whole" and the rise in trading volume to "a lack of consensus regarding the price." When an announcement is released, almost everyone in the market would understand at least some of the price implications -- the direction of prices, for example -- and prices should move sharply to reflect this common understanding even without any trading. The precise magnitude of the appropriate price change, however, would be a matter of analysis or interpretation, which would differ among investors. Given some heterogeneity of views conditional on the announcement, some investors would see the initial price adjustment as an overreaction, others as an underreaction. These investors would then take positions on the strength of their views and thus produce the volume surge.

In the recent price formation literature, a number of formal models show that some form of heterogeneity of views among investors can generate speculative trading activity. To account specifically for surges in volume following public announcements, Kim and Verrecchia (1991) assume investor idiosyncrasies, Foster and Viswanathan (1993) represent beliefs with elliptically contoured distributions, Harris and Raviv (1993) rely on differences in opinion, and Kandel and Pearson (1995) specify agents with different likelihood functions. Note, however, that the phenomenon we would like to explain is not just the fact that volume surges after a public announcement but that it surges *only after the*

initial price adjustment that follows the announcement. These models take no account of the bid-ask spread, and a lack of liquidity at the time of the announcement may help explain the apparent trading pause.

Hypothesis 3: The price-volume relationship reflects a sluggishness in the formation of a consensus price

The persistence of high and declining price volatility along with high and declining trading volume suggests a slow process of price adjustment to reconcile the heterogeneous views of investors. The hypothesis assumes that the consensus price that ultimately prevails corresponds to a weighted average of the various investors' views. Investors partially reveal their views by trading when the market price deviates significantly from their forecasts of the consensus price. In making their forecasts, individual investors rationally put some weight on their own views and some weight on the market price at the time. The deviations between the market price and individual forecasts would tend to be widest after the initial price adjustment following the announcement, and speculative trades would be correspondingly large.

It is an important part of the hypothesis that not all investors trade to fully reveal their views at once so that a consensus price is not reached quickly. The difficulty of establishing a consensus price would arise from noise in prices and trades that serve to obscure traders' views. Such noise may come from strategic trading by dealers or from the use of customers' liquidity trades to disguise speculative trades. Thus the market price adjusts sluggishly over time to reflect the views of more investors more closely at the same time that investors revise their forecasts to put more weight on the market price and less on their own initial views. Deviations between price and forecast slowly narrow and speculative trades decrease. In this way, we would observe high and declining

volume with high and declining volatility until the convergence to a consensus price.

He and Wang's (1995) model of differentially informed investors is one that gives rise to a slow convergence to a consensus price along with persistent trading volume.[34] In their model, investors trade for several rounds after they receive information. Hence, volume and volatility persist even when the arrival of information does not. Such persistence is possible because prices are noisy and not fully revealing of all the traders' information. He and Wang, however, base these results on differential private information. When they analyze the effects of public announcements, they find that investors take speculative positions before the announcements and unwind those positions immediately afterwards. We find little evidence of such effects in the U.S. Treasuries market. The investors in this market seem more willing to bet on the consensus price conditional on an announcement than on the announcement itself. Our stylized facts are more consistent with He and Wang's private information story, with such information interpreted as private views induced by a public announcement.

We have more difficulty interpreting our results in terms of the mixture-of-distributions hypothesis advanced by Clark (1973), Epps and Epps (1976), Tauchen and Pitts (1983), and Lamoureux and Lastrapes (1990). The hypothesis explains serial correlation in volatility and the price-volume relationship in terms of the arrival of new information. The explanation is consistent with the idea that private information is conveyed to prices through trading. Serial correlation

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[34] Foster and Viswanathan's (1996) model of strategic trading with agents forecasting one another's forecasts contains elements consistent with our hypothesis. Strategic behavior is one way to prevent prices and trade flows from fully revealing investors' private forecasts. However, they focus on the correlation structures of information signals rather than on price-volume relationships.

in volume would require a sequential flow of new information.[35] While such information flow may be possible, it is hard to conceive of the special kind of new information that would produce not just the persistence of high volatility and high volume but the consistent decline of volatility and volume over time following public announcements.

Hypothesis 4: Inventory risk control drives liquidity

The brief period of illiquidity around a major announcement is consistent with the behavior of competing dealers who are simply trying to control the risks in their inventories. In this market, dealers face risk arising from the uncertainty about returns on their inventories and from the uncertainty about transaction flows. The effort to control risk would cause them to quote an extraordinarily wide spread at the time of major announcements in anticipation of the high price volatility. Once the announcement is out, they would begin to quote a much narrower spread in spite of continued high price volatility because the ensuing surge in trading volume greatly reduces the transaction flow uncertainty.

In the microstructure literature, recent models of market making based on asymmetric information have challenged the more traditional models based on inventory control. The inventory-control models of Demsetz (1968), Tinic and West (1972), Amihud and Mendelson (1980), and Ho and Stoll (1983) emphasize the increased risk to market makers of high price volatility and low trading volume. Market makers' efforts to control this risk result in a positive relationship between the bid-ask spread and volatility or other measures of price

[35] Bollerslev, Chou, and Kroner (1992) call for an explanation of "serial correlation in conditional second moments" as a property of speculative prices. The mixture-of-distributions hypothesis with serially correlated information flows is a possible explanation. Jones, Lamont, and Lumsdaine (1996) find some support for this explanation at daily frequencies. Our hypothesis of a slow convergence to a consensus price after the arrival of information offers an alternative explanation for intraday serial correlation.

risk and a negative relationship between the spread and volume. The asymmetric-information models of Glosten and Milgrom (1985), Kyle (1985), Admati and Pfleiderer (1988), and Easley and O'Hara (1992), however, emphasize the risk to market makers of dealing with investors with superior information. As a result, market makers would set the spread based on when the informed and uninformed trade. Admati and Pfleiderer, for example, propose that discretionary liquidity traders would cluster their trading activity around certain times of the day and that the resulting liquidity would attract the informed investors who would in turn bring price volatility. Hence high volume, high volatility, and narrow spreads would coincide.

The evidence from the U.S. Treasuries market lends support to the traditional inventory control models of the bid-ask spread. To see this, we regress the spread on concurrent and anticipated next-period price volatility and trading volume. For anticipated volatility and volume, we use the predicted values from the regressions reported in Table II, which use announcement dummy variables as explanatory variables. We run the regression on a panel of five-minute intervals across our full sample of 250 trading days. The estimated regression is

$$s_t = 1.494 + 1.029\, p_t + 0.756\, E_t(p_{t+1}) - 0.027\, v_t - 0.026\, E_t(v_{t+1})$$

where s_t is the bid-ask spread, p_t is price volatility, v_t is trading volume, and $E_t(p_{t+1})$ and $E_t(v_{t+1})$ are anticipated volatility and volume for the next five-minute interval.[36] Each coefficient is significantly different from zero at the 1% level and the adjusted R-squared statistic is 0.107. The slope coefficients have the expected signs: the spread widens with both concurrent and anticipated

[36] The bid-ask spread is measured in hundredths of a percent, price volatility is the change in log prices times a thousand, and trading volume is measured in tens of millions of U.S. dollars.

price volatility and narrows with both concurrent and anticipated trading volume.

The performance of the regression across time intervals suggests that the way the competing dealers set the spread around announcement times is similar to the way they set it at other times of the day. Such consistency would not be so apparent if asymmetric information was important. Figure 6 compares the regression's prediction of the bid-ask spread to the actual spread. The *actual difference* is the difference between the mean spread on days with major 8:30 AM announcements and the mean spread on nonannouncement days. The *predicted difference* is the difference between the mean predicted spread on announcement days and the mean spread on nonannouncement days. The figure shows that our model performs consistently well in explaining the average spread before a major announcement, around the announcement, and after the announcement.

To explain the spread's dramatic behavior around major announcements, Figure 6 also presents two other predicted spread measures. *Predicted difference with usual trading volume* is the difference between the mean predicted spread on announcement days assuming trading volume did not increase and the mean spread on nonannouncement days. This counterfactual measure shows that the bid-ask spread would likely have stayed high on major announcement days had trading volume not also increased with price volatility. *Predicted difference with usual price volatility* is the difference between the mean predicted spread on announcement days assuming price volatility did not increase and the mean spread on nonannouncement days. This counterfactual measure shows that the bid-ask spread would have been even lower on announcement days had the high trading volume that accompanies major announcements not also been accompanied by high price volatility. The rapid decline of the bid-ask spread in

spite of continuing high price volatility seems to result from the offsetting effects of high trading volume.

Hypothesis 5: Liquidity traders react with a lag to price changes

To explain why high volumes persist for a longer period than high volatilities, we propose that certain liquidity traders react to price changes. In existing microstructure models, liquidity traders do not need to react to price changes; they trade for purely exogenous reasons. In the bond market, however, there are good reasons for a reaction. Investment strategies that involve duration targets and dynamic hedging strategies for swaps, options, and mortgage-backed securities require a reaction to price changes. In theory the reaction should be continuous, but in practice transactions costs lead to an optimal reaction lag. Investors following these strategies are liquidity traders in the sense that they do not speculate on prices and their trades would not cause price volatility. Having an optimal reaction lag limits their discretion over when they may trade during the day. Some liquidity traders may begin to react as soon as the bid-ask spread narrows with the surge in volume after an announcement, but with continued volatility some of them would still be reacting later in the day. Some liquidity traders may react with lags of half an hour or longer, generating high volumes even after volatility has returned to normal levels.

Our data provide evidence that price volatility leads to trading volume. Table VI reports Granger causality tests of volume and volatility based on six lags of five-minute intervals for our full sample of trading days.[37] The tests confirm a persistence in volatility controlling for past volume and a persistence of volume controlling for past volatility. More interestingly, the tests also show

[37] Volatility is the absolute change in log prices times a thousand and volume is measured in tens of millions of U.S. dollars.

that volatility causes subsequent volume and to a lesser extent that volume causes subsequent volatility. The former is consistent with our hypothesis of liquidity traders reacting with a lag to price changes.[38] Similar evidence of a persistence of high volume beyond the period of high volatility has been found in the stock market by Beaver (1968), Morse (1981), Jain and Joh (1988), and Gallant, Rossi, and Tauchen (1992).[39] Such evidence in the stock market may also be explained by liquidity traders who react to price changes.

VII. Conclusion

The recent availability of data on the interdealer U.S. Treasuries market allows us to examine in a new light how secondary markets form prices and provide liquidity. The market we study is an extremely liquid one where many dealers compete as both market makers and informed investors. We focus the examination on intraday patterns around the times of macroeconomic announcements, because they identify precise times for the arrival of information in the market. In the body of the paper, we describe our most striking results in the form of five stylized facts and we discuss various hypotheses to explain them separately. In this section, we recapitulate by pulling the facts and hypotheses together.

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[38] An alternative hypothesis is that the longer persistence of volume reflects the unwinding of speculative positions later in the day. In theory dealers should be able to execute such unwinding without causing price volatility and in practice such execution would be made easier by the presence of liquidity traders.

[39] Karpoff (1987, p. 123) finds such evidence puzzling, paticularly because it "casts doubt on the interpretation of volume statistics as measures of 'information content' in event studies."

Our analysis suggests that the announcements set off an extended price formation process. The sharpest price adjustments take place in the first few moments of the process, when prices adjust to reflect public rather than private information. We infer that the information is indeed public because we see no rise in trading activity. From then on, the price formation process continues but with a new shape, in which further price adjustment is accompanied by a surge in trading volume. We believe this continuation of the process is driven by an initially wide disagreement among investors about what the new information means for prices. We do not think a sequential arrival of private information can easily explain why the process should follow the release of public information and involve a steady decline in volatility and volume. To us, the process looks like a process of convergence toward a consensus price.

The persistence of high volatility and high volume suggests a rather sluggish convergence process. Even so liquid a market seems to have great difficulty resolving disagreement among investors. He and Wang's (1995) model shows that such a sluggish process is at least a theoretical possibility. The source of the difficulty is not that views are held stubbornly, since the consensus price that ultimately prevails should reflect all the views. The difficulty arises from noise in prices and trades that serves to obscure investors' views from one another. The noise may come from strategic trading by dealers or from the use of customers' liquidity trades to disguise speculative trades.

The moments in which prices adjust sharply to public information are also among the few times the market suffers from some illiquidity. These are the moments of the widest bid-ask spreads away from the start and end of the trading day. The dealers hesitate to provide liquidity simply because of the uncertainty about the price changes immediately following the announcement and not because of the risk of trading with better informed investors. The

asymmetric information assumption is inconsistent with the notion that the price changes during these moments arise from public information. Indeed, the dealers soon become willing to provide liquidity at the very time when a surge in volume and high volatility might suggest trading by better informed investors. Instead of widening, the bid-ask spread narrows. We believe the spread narrows because the volume arises from speculative trading by investors who disagree on the price adjustment as well as from liquidity trading by investors who react with a lag to the price changes.

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Appendix A: **Primary Government Securities Dealers**
(as of October 1996)

BA Securities, Inc.
Barclays de Zoete Wedd Securities Inc.
Bear, Stearns & Co., Inc
BT Securities Corporation
Chase Securities Inc.
CIBC Wood Gundy Securities Corp.
Citicorp Securities, Inc.
CS First Boston Corporation
Daiwa Securities America Inc.
Dean Witter Reynolds Inc.
Deutsche Morgan Grenfell/C.J. Lawrence Inc.
Dillon, Read & Co. Inc.
Donaldson, Lufkin & Jenrette Securities Corporation
Eastbridge Capital Inc.
First Chicago Capital Markets, Inc.
Fuji Securities Inc.
Goldman, Sachs & Co.
Greenwich Capital Markets, Inc.
HSBC Securities, Inc.
Aubrey G. Lanston & Co., Inc.
Lehman Brothers Inc.
Merrill Lynch Government Securities Inc.
J.P. Morgan Securities, Inc.
Morgan Stanley & Co. Incorporated
NationsBanc Capital Markets, Inc.
Nesbitt Burns Securities Inc.
The Nikko Securities Co. International, Inc.
Nomura Securities International, Inc.
Paine Webber Incorporated
Prudential Securities Incorporated
Salomon Brothers Inc.
Sanwa Securities (USA) Co., L.P.
Smith Barney Inc.
SBC Capital Markets Inc.
UBS Securities LLC
Yamaichi International (America), Inc.
Zions First National Bank

Appendix B: **Data Cleaning and Processing**

GovPX distributes its information through on-line vendors by sending out a digital ticker feed. Daily backup copies of the feed are used in this study. The data provides a precise history of the tick-by-tick trading information sent to GovPX subscribers. Any posting errors made by the interdealer brokers that are not filtered out by GovPX are of course included in the backup files. Additionally, since the purpose of the digital feed is to refresh vendors' screens, the data must be processed before it can be effectively analyzed.

Trades

When a trade occurs two pieces of information are typically transmitted by GovPX. First, during the "work-up" stage when traders are jumping into a transaction, the news is posted that a bid is being "hit" or that an offer is being lifted (a "take"), as are price and volume information. Seconds later the total volume of the trade or trades is posted. Transactions through the same interdealer broker at the same price and virtually the same time are thus counted as a single trade. Occasionally GovPX posts several lines of data per trade, and sometimes there is only a single line.

The volume data is processed to ensure that each trade is counted once and only once. This is done by retaining the price and volume data from the first line reporting an increase in total daily volume for that security. This is typically the second line of data reported for any given trade since the first line usually reports only that a trade is occurring (with no trade size or increase in daily volume reported) . In our year of intraday data there are a few instances where total daily volume shows a trade-to-trade *decline* for the on-the-run 5-year note. These errors are corrected based on that day's history of trades and the total daily volume reported for that security.[40] In our year of data we find 164,822 trades for the on-the-run 5-year note, or an average of 659 per day.

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[40] For example, at 3:32 PM eastern time (ET) on September 28, 1993 GovPX reports an unprecedented trade of $810 million. Seventy minutes later GovPX reports a decline in accumulated volume of $807 million for that same security. The size of the trade, its subsequent

Quotations

We put bid-ask quotes through a multi-step screening procedure:

- Bid price movements of at least 3/4 of a point that are followed by a similarly sized movement in the opposite direction (within 25%) are dropped. This screen is imposed as several instances were found where a security was erroneously reported to have moved a full point followed by a full point correction within minutes. This eliminates an average of 0.3 quotes per day.
- As offers (or asks) in the dataset are quoted off of the bids, large positive spreads are indistinguishable from small negative spreads. Spreads calculated to be greater than 0.9 point (and less than 1.0 point) are likely to be either errors or negative spreads that existed only momentarily when quotes arrived from two different brokers. These quotes (22 per day) are dropped.
- One-sided quotes (a bid *or* an offer but not both) are occasionally posted by dealers. This study makes no use of these bids (22 per day) or offers (18 per day).
- Finally, spreads with bid-ask midpoints more than 10 standard deviations from the daily bid-ask midpoint mean or daily price mean are dropped as are spreads more than 10 standard deviations from the daily spread mean. This screens out 1.5 quotes per day.

As spreads posted by the interdealer brokers do not include the brokerage fee charged to the transaction initiator, zero spreads are common and can persist for lengthy periods. Quotes calculated to be zero are therefore kept in the dataset. Our dataset retains 541,745 quotes from the sample period for the on-the-run 5-year note, or an average of 2,167 per day.

Times

GovPX's digital ticker feed contains a minute-by-minute time stamp. The stamps typically appear 60 seconds apart within a day, but the exact timing of the stamp varies across the days. One day may have time stamps of 8:28:40, 8:29:40, 8:30:40, etc. while another day has time stamps of 8:28:53, 8:29:53, 8:30:53, etc. In our analysis each

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reversion (as measured by accumulated volume), and the daily total volume statistic (reported in a separate file) all suggest that the original trade was an error. We therefore scale down the original trade size by the size of the reversion ($807 million).

interval is assumed to start at the beginning of the new minute that starts in that interval. Our 8:30-35 interval therefore refers to the five minute period starting between 8:29 and 8:30 and ending five minutes later between 8:34 and 8:35, while our 8:30-31 interval refers to the one-minute period starting between 8:29 and 8:30 and ending between 8:30 and 8:31.

Missing time stamps on a few of our sample days indicate times when we are missing data. The most serious case of missing data in our sample is December 10, 1993 when our daily file ends at 12:10 PM (ET) instead of 6:00 PM. Most of our periods of missing data occur outside of New York trading hours (7:30 AM - 5:00 PM), however, and none appear within even a few hours of one our announcements.

Time Intervals

For tractability purposes our data is consolidated and analyzed at the five-minute or one-minute interval. While the on-the-run 5-year note is the most actively traded Treasury security, we are nevertheless missing some bid-ask spread and price volatility observations.[41] Specifically, the bid-ask spread is defined for 98.2% of the five-minute trading intervals in our sample.[42] As our definition of price volatility is based on the change in price between successive intervals, this variable is defined for a slightly lower 96.9% of five-minute trading intervals. Not surprisingly, most of our missing observations are either early in the morning (7:30 - 8:00 AM) or late in the afternoon (4:00 PM - 5:00 PM) when trading activity is light.[43] Looking at the one-minute interval, we have bid-ask spread (price volatility) observations for 94.1% (89.2%) of the trading intervals on which we focus our one-minute analysis (8:25 - 8:37 AM).

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[41] There are no missing observations for trading volume as it is defined to be zero when there are no transactions in an interval.

[42] We count trading intervals as the number of five-minute intervals between 7:30 AM (ET) and the market close for our 250 day sample. The market close is defined as the time of the last bid-ask quotation (for the on-the-run 5-year note) for days when the market closed early and 5:00 PM otherwise.

[43] In the one hour period (8:20 AM - 9:20 AM) around the important 8:30 AM announcements, we have bid-ask spread (price volatility) observations for 99.97% (99.77%) of the trading intervals.

Holidays

We exclude 10 days from our sample when the Treasuries market was closed. The market was closed on nine of these days in recognition of a holiday and on one day (April 27, 1994) for the funeral of President Nixon.[44] We retain one day in our sample, April 1, 1994 (Good Friday), when the Public Securities Association (an industry trade group) recommended that the bond market stay closed. The release of the March employment report that day resulted in significant morning trading volume. We also retain several days in our sample when the market closed early (e.g., 2:00 PM), typically before a holiday.

[44] GovPX recorded at least some overseas trading on five of these days and on two of the days some light trading occurred during morning trading hours in New York.

Table I

Macroeconomic Announcements

Announcement time, title, and reporting entitities for eighteen monthly macroeconomic announcements and one weekly (initial jobless claims) macroeconomic announcement. All times are eastern time (ET).

Time	Short Title	Full Title	Reporting Entity
8:30 A.M.	Consumer Price Index (CPI)	Consumer Price Index	Bureau of Labor Statistics
8:30 A.M.	Durable Goods Orders	Advance Report on Durable Goods Manufacturers' Shipments and Orders	Bureau of the Census
8:30 A.M.	Employment	The Employment Situation	Bureau of Labor Statistics
8:30 A.M.	Gross Domestic Product (GDP)	Gross Domestic Product	Bureau of Economic Analysis
8:30 A.M.	Housing Starts	Housing Starts and Building Permits	Bureau of the Census
8:30 A.M.	Initial Jobless Claims	Initial Jobless Claims	Bureau of Labor Statistics
8:30 A.M.	Leading Indicators	Composite Indexes of Leading, Coincident, and Lagging Indicators	Bureau of Economic Analysis
8:30 A.M.	Merchandise Trade	Report of U.S. Merchandise Trade	Bureau of the Census
8:30 A.M.[a]	Personal Income	Personal Income and Outlays	Bureau of Economic Analysis
8:30 A.M.	Producer Price Index (PPI)	Producer Price Indexes	Bureau of Labor Statistics
8:30 A.M.	Retail Sales	Advance Retail Sales	Bureau of the Census
9:15 A.M.	Industrial Production and Capacity Utilization	Industrial Production and Capacity Utilization	Federal Reserve Board
10:00 A.M.	Business Inventories	Manufacturing and Trade: Inventories and Sales	Bureau of the Census
10:00 A.M.	Consumer Confidence	Consumer Confidence Index	Conference Board
10:00 A.M.	Construction Spending	Value of New Construction Put in Place	Bureau of the Census
10:00 A.M.	Factory Inventories	Manufacturers' Shipments, Inventories, and Orders	Bureau of the Census
10:00 A.M.	NAPM Survey	National Association of Purchasing Management Index	National Association of Purchasing Management
10:00 A.M.	New Single-Family Home Sales	New One-Family Houses Sold and For Sale	Bureau of the Census
2:00 P.M.	Federal Budget	Treasury Statement (The Monthly "Budget")	Department of the Treasury

[a] Personal income was reported at 10:00 A.M. for the first four announcements in the period of analysis and at 8:30 A.M. thereafter.

Table II

The Impact of Announcements on Price Volatility, Trading Volume, and Bid-Ask Spreads for the Five-Year Treasury Note

Regressions of price volatility, trading volume, and bid-ask spread on announcement dummy variables for the five-year treasury note.[a] Results are presented for four five-minute intervals (Panels A, B, C, and D) corresponding to the four sets of announcement times from Table I. For price volatility and the bid-ask spread the five-minute period immediately following the announcements is presented (e.g., 8:30-8:35 for the 8:30 A.M. announcements), while for trading volume the succeeding five-minute period is presented (e.g., 8:35-8:40 for the 8:30 A.M. announcements). The Panel B, C, and D regressions were run including dummy variables for announcements that are reported earlier in the day, although these coefficients are excluded from the table. One and two asterisks indicate significance at the .05 and .01 levels, respectively. The period of analysis is August 23, 1993 - August 19, 1994.

	Price Volatility		Trading Volume		Bid-Ask Spread	
	Regression Coefficient	P-Value	Regression Coefficient	P-Value	Regression Coefficient	P-Value
Panel A: 8:30 A.M. Announcements						
Intercept	0.223**	0.001	7.717**	0.001	1.623**	0.001
Consumer Price Index	0.783**	0.001	4.443*	0.045	1.178**	0.001
Durable Goods Order	0.073	0.732	0.601	0.781	0.737**	0.006
Employment	2.625**	0.001	18.159**	0.001	3.189**	0.001
Gross Domestic Product	0.732**	0.001	4.210*	0.043	0.851**	0.001
Housing Starts	0.116	0.573	3.489	0.093	0.481	0.060
Initial Jobless Claims	0.143	0.194	2.492*	0.025	0.386**	0.005
Leading Indicators	-0.320	0.126	-0.148	0.944	0.213	0.413
Merchandise Trade	0.217	0.298	1.945	0.355	0.663*	0.011
Personal Income	0.230	0.356	-1.273	0.612	0.737*	0.018
Producer Price Index	1.401**	0.001	7.875**	0.001	0.976**	0.001
Retail Sales	0.633**	0.006	6.705**	0.004	0.601*	0.035
Adjusted R^2	0.480		0.298		0.462	

Table II - Continued

Panel B: 9:15 A.M. Announcements						
Intercept	0.152**	0.001	6.038**	0.001	1.397**	0.001
Industrial Production and Capacity Utilization	0.358**	0.001	4.823**	0.005	0.632**	0.001
Adjusted R^2	0.215		0.167		0.107	
Panel C: 10:00 A.M. Announcements						
Intercept	0.163**	0.001	6.012**	0.001	1.302**	0.001
Business Inventories	0.075	0.480	3.570	0.063	0.414*	0.020
Construction Spending-NAPM Survey[b]	0.652**	0.001	8.440**	0.001	0.559**	0.001
Consumer Confidence	0.353**	0.001	3.900*	0.023	0.416**	0.009
Factory Inventories	0.061	0.537	4.092*	0.022	0.151	0.357
New Single-Family Home Sales	0.307**	0.004	6.049**	0.002	0.821**	0.001
Personal Income	-0.195	0.238	1.948	0.512	-0.292	0.288
Adjusted R^2	0.186		0.181		0.202	
Panel D: 2:00 P.M. Announcements						
Intercept	0.189**	0.001	4.629**	0.001	1.526**	0.001
Federal Budget	0.006	0.893	-1.100	0.415	0.037	0.833
Adjusted R^2	-0.020		0.019		-0.013	

a Price volatility is defined as the absolute value of the log price change times 10^3. Trading volume is reported in tens of millions of U.S. dollars. The bid-ask spread equals the actual bid-ask spread times 10^4.

b Construction spending and NAPM Survey are combined into a single dummy variable since they were released at the same time ten of twelve times in the sample. The dummy variable is set equal to one for days when both reports were released, ½ for days when only one report was released, and zero otherwise.

Table III

Persistence of Price Volatility, Trading Volume, and Bid-Ask Spread by One-Minute Intervals

One-minute log price change standard deviation, trading volume mean, and bid-ask spread mean are reported and compared for announcement (major 8:30 A.M.) and nonannouncement days for the five-year treasury note.[a] All one-minute intervals between 8:25 and 8:37 A.M. are reported. One and two asterisks denote significance at the .05 and .01 levels, respectively. The period of analysis is August 23, 1993 - August 19, 1994.

	8:25-8:26	8:26-8:27	8:27-8:28	8:28-8:29	8:29-8:30	8:30-8:31	8:31-8:32	8:32-8:33	8:33-8:34	8:34-8:35	8:35-8:36	8:36-8:37
Panel A: Price Volatility												
Announcement day[b]	0.114	0.131	0.116	0.131	0.292	1.486	1.336	0.509	0.558	0.450	0.292	0.295
Nonannouncement day[c]	0.109	0.116	0.090	0.110	0.103	0.118	0.127	0.088	0.103	0.119	0.102	0.102
Standard Deviation Ratio	1.041	1.122	1.279	1.190	2.841**	12.557**	10.556**	5.800**	5.425**	3.796**	2.867**	2.893**
F-ratio p-value[d]	0.914	0.715	0.296	0.389	0.008	0.001	0.001	0.001	0.001	0.002	0.001	0.001
Panel B: Trading Volume												
Announcement day	1.256	1.156	1.067	1.019	0.919	1.112	1.074	2.981	3.372	4.698	3.940	5.026
Nonannouncement day	1.340	1.183	1.609	1.370	1.066	1.359	1.584	1.320	1.459	1.159	1.247	1.379
Difference in Means	-0.084	-0.027	-0.542	-0.351	-0.148	-0.248	-0.509	1.662**	1.913**	3.538**	2.693**	3.647**
t-statistic p-value[e]	0.809	0.926	0.073	0.193	0.497	0.546	0.071	0.001	0.001	0.001	0.001	0.001
Panel C: Bid-Ask Spread												
Announcement day	1.998	1.903	2.095	2.210	2.691	7.343	5.469	2.945	2.410	1.654	1.757	1.731
Nonannouncement day	1.627	1.590	1.633	1.490	1.453	1.489	1.463	1.322	1.501	1.563	1.549	1.578
Difference in Means	0.371	0.313	0.462*	0.720**	1.239**	5.854**	4.006**	1.623**	0.909	0.091	0.208	0.152
t-statistic p-value	0.087	0.096	0.016	0.001	0.001	0.001	0.001	0.001	0.055	0.573	0.209	0.283

[a] The reported log price change standard deviation is the actual standard deviation times 10^3. Trading volume is reported in tens of millions of U.S. dollars. The reported bid-ask spread is the actual spread times 10^4.

[b] Announcement days are defined as days with at least one of the following announcements: Consumer Price Index, Employment, Gross Domestic Product, Producer Price Index, Retail Sales. These are the 8:30 A.M. announcements significant at the .01 level in at least two models of Table II. Excluded are days in which there are any of our 9:15 A.M. or 10:00 A.M. announcements.

[c] Nonannouncement days are defined as days in which none of our eighteen morning announcements occur.

[d] P-value from Brown-Forsythe-modified Levene F-statistic comparing variances for announcement and nonannouncement days.

[e] P-value from t-statistic comparing means for announcement and nonannouncement days assuming unequal variances.

Table IV

Persistence of Price Volatility, Trading Volume, and Bid-Ask Spread by Five-Minute Intervals

Five-minute log price change standard deviation, trading volume mean, and bid-ask spread mean are reported and compared for announcement (major 8:30 A.M.) and nonannouncement days for the five-year treasury note.[a] All five-minute intervals between 8:15 and 8:45 A.M. are reported as well as intervals from every fifteen minutes between 9:00 and 10:30 A.M.. One and two asterisks denote significance at the .05 and .01 levels, respectively. The period of analysis is August 23, 1993 - August 19, 1994.

	8:15-8:20	8:20-8:25	8:25-8:30	8:30-8:35	8:35-8:40	8:40-8:45	9:00-9:05	9:15-9:20	9:30-9:35	9:45-9:50	10:00-10:05	10:15-10:20
Panel A: Price Volatility												
Announcement day[b]	0.221	0.215	0.385	2.387	0.922	0.506	0.408	0.337	0.227	0.273	0.358	0.234
Nonannouncement day[c]	0.209	0.267	0.219	0.212	0.239	0.219	0.179	0.197	0.179	0.178	0.197	0.249
Std. Deviation Ratio	1.055	0.804	1.754	11.284**	3.865**	2.312**	2.276**	1.710**	1.265*	1.534**	1.822**	0.941
F-ratio p-value[d]	0.967	0.237	0.060	0.001	0.001	0.001	0.001	0.001	0.038	0.003	0.009	0.353
Panel B: Trading Volume												
Announcement day	4.174	5.493	5.416	13.237	19.405	15.767	13.309	10.402	9.353	8.658	8.705	8.047
Nonannouncement day	3.224	5.702	6.567	6.881	7.063	6.817	5.064	5.187	5.791	5.559	5.917	6.013
Difference in Means	0.950	-0.209	-1.151	6.356**	12.342**	8.950 **	8.245**	5.215**	3.563**	3.099**	2.787**	2.034*
t-statistic p-value[e]	0.176	0.757	0.098	0.001	0.001	0.001	0.001	0.001	0.001	0.005	0.003	0.035
Panel C: Bid-Ask Spread												
Announcement day	1.773	1.832	2.160	3.313	1.706	1.487	1.614	1.479	1.442	1.343	1.573	1.456
Nonannouncement day	1.754	1.636	1.550	1.478	1.470	1.404	1.471	1.424	1.376	1.300	1.237	1.335
Difference in Means	0.019	0.196	0.610**	1.836**	0.236*	0.083	0.144	0.055	0.066	0.043	0.336**	0.121
t-statistic p-value	0.902	0.133	0.001	0.001	0.031	0.394	0.151	0.472	0.458	0.588	0.001	0.177

[a] The reported log price change standard deviation is the actual standard deviation times 10^3. Trading volume is reported in tens of millions of U.S. dollars. The reported bid-ask spread is the actual spread times 10^4.

[b] Announcement days are defined as days with at least one of the following announcements: Consumer Price Index, Employment, Gross Domestic Product, Producer Price Index, Retail Sales. These are the 8:30 A.M. announcements significant at the .01 level in at least two models of Table II. Excluded are days in which there are any of our 9:15 A.M. or 10:00 A.M. announcements.

[c] Nonannouncement days are defined as days in which none of our eighteen morning announcements occur.

[d] P-value from Brown-Forsythe-modified Levene F-statistic comparing variances for announcement and nonannouncement days.

[e] P-value from t-statistic comparing means for announcement and nonannouncement days assuming unequal variances.

Table V

Correlations of Price Volatility and Trading Volume

Correlations of price volatility (absolute value of log price change) and trading volume for the five-year treasury note. All one-minute intervals between 8:25 and 8:49 A.M. are reported. One and two asterisks denote significance at the .05 and .01 levels, respectively. The period of analysis is August 23, 1993 - August 19, 1994.

	8:25-8:26	8:26-8:27	8:27-8:28	8:28-8:29	8:29-8:30	8:30-8:31	8:31-8:32	8:32-8:33	8:33-8:34	8:34-8:35	8:35-8:36	8:36-8:37
Correlation	0.223**	0.189**	0.169*	0.195**	0.229**	0.049	-0.072	0.348**	0.298**	0.117	0.261**	0.169*
p-value	0.001	0.006	0.013	0.004	0.001	0.474	0.282	0.001	0.001	0.079	0.001	0.011
	8:37-8:38	8:38-8:39	8:39-8:40	8:40-8:41	8:41-8:42	8:42-8:43	8:43-8:44	8:44-8:45	8:45-8:46	8:46-8:47	8:47-8:48	8:48-8:49
Correlation	0.221**	0.234**	0.283**	0.107	0.156*	0.274**	0.251**	0.270**	0.344**	0.116	0.195**	0.139*
p-value	0.001	0.001	0.001	0.106	0.019	0.001	0.001	0.001	0.001	0.083	0.004	0.037

Table VI

Granger Causality Tests of Trading Volume and Price Volatility

Results from Granger causality tests of trading volume and price volatility for the five-year treasury note. Tests are conducted for New York trading hours (7:30 A.M. - 5:00 P.M.) using six lags of both price volatility and trading volume. Variables are measured in five-minute intervals with price volatility defined as the absolute value of the log price change times 10^3 and trading volume measured in tens of millions of U.S. dollars. One and two asterisks denote significance at the .05 and .01 levels, respectively. The period of analysis is August 23, 1993 - August 19, 1994.

Question	Dependent variable	Lagged variables	Sum of coefficients	F-statistic	p-value
Is price volatility persistent?	price volatility	price volatility	0.472	306.219**	0.001
Is trading volume persistent?	trading volume	trading volume	0.619	852.323**	0.001
Does price volatility cause trading volume?	trading volume	price volatility	6.501	183.752**	0.001
Does trading volume cause price volatility?	price volatility	trading volume	0.003	18.578**	0.001

Figure 1A

Intraday Price Volatility for the Five-Year Treasury Note

Standard deviation of log price changes by five-minute interval from August 23, 1993 - August 19, 1994. The standard deviation equals the actual standard deviation times 1000 and times shown are interval start times eastern time (ET).

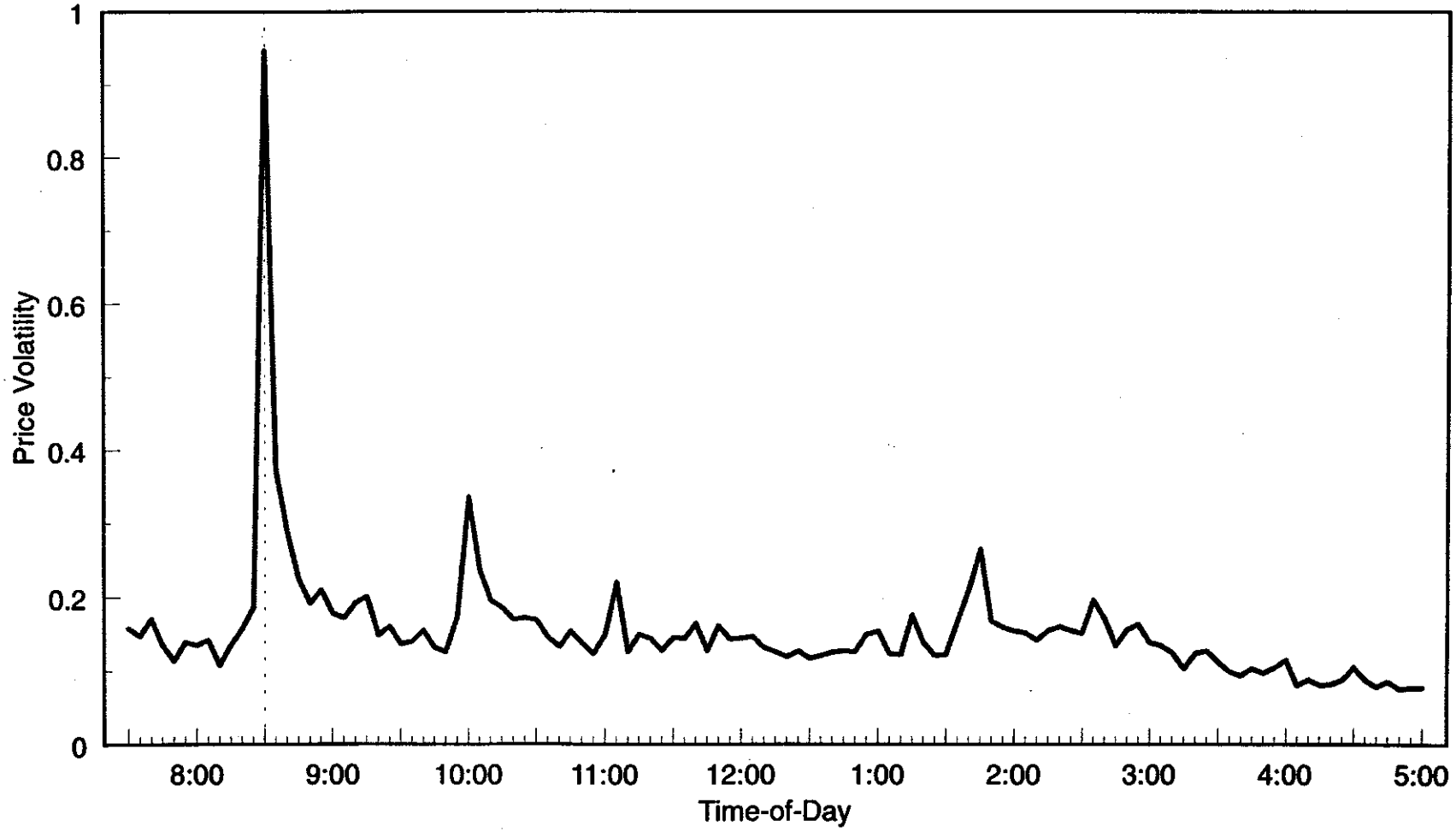


Figure 1B

Intraday Price Volatility on Announcement and Nonannouncement Days

Standard deviation of log price changes for the five-year treasury note for days with at least one of the nineteen announcements listed in Table I and days with none of these announcements. The standard deviation equals the actual standard deviation times 1000, the period of analysis is August 23, 1993 - August 19, 1994, and times shown are interval start times (ET).

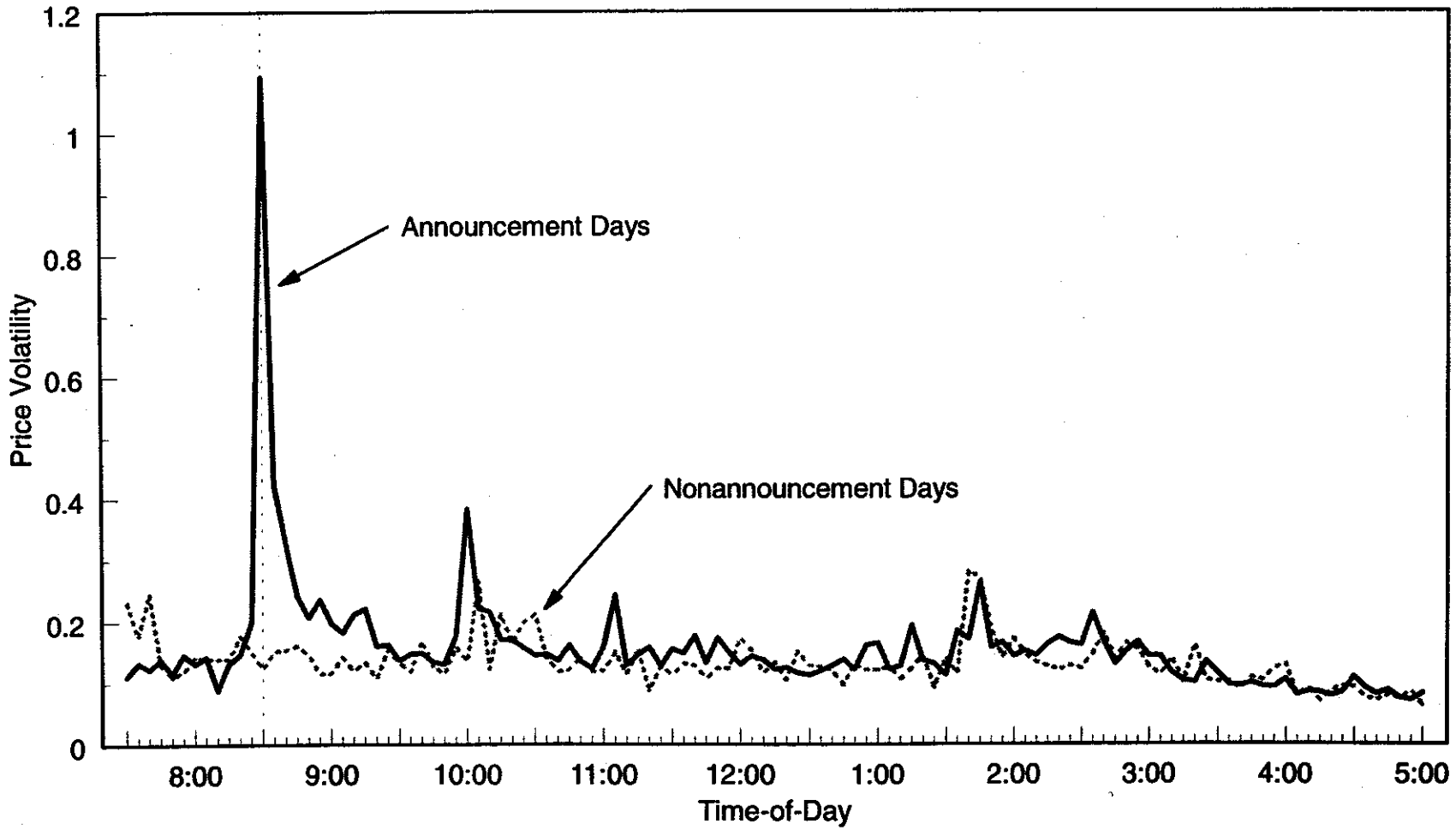


Figure 2A

Intraday Trading Volume for the Five-Year Treasury Note

Mean interdealer trading volume by five-minute interval from August 23, 1993 - August 19, 1994. Trading volume is reported in tens of millions of U.S. dollars and times shown are interval start times (ET).

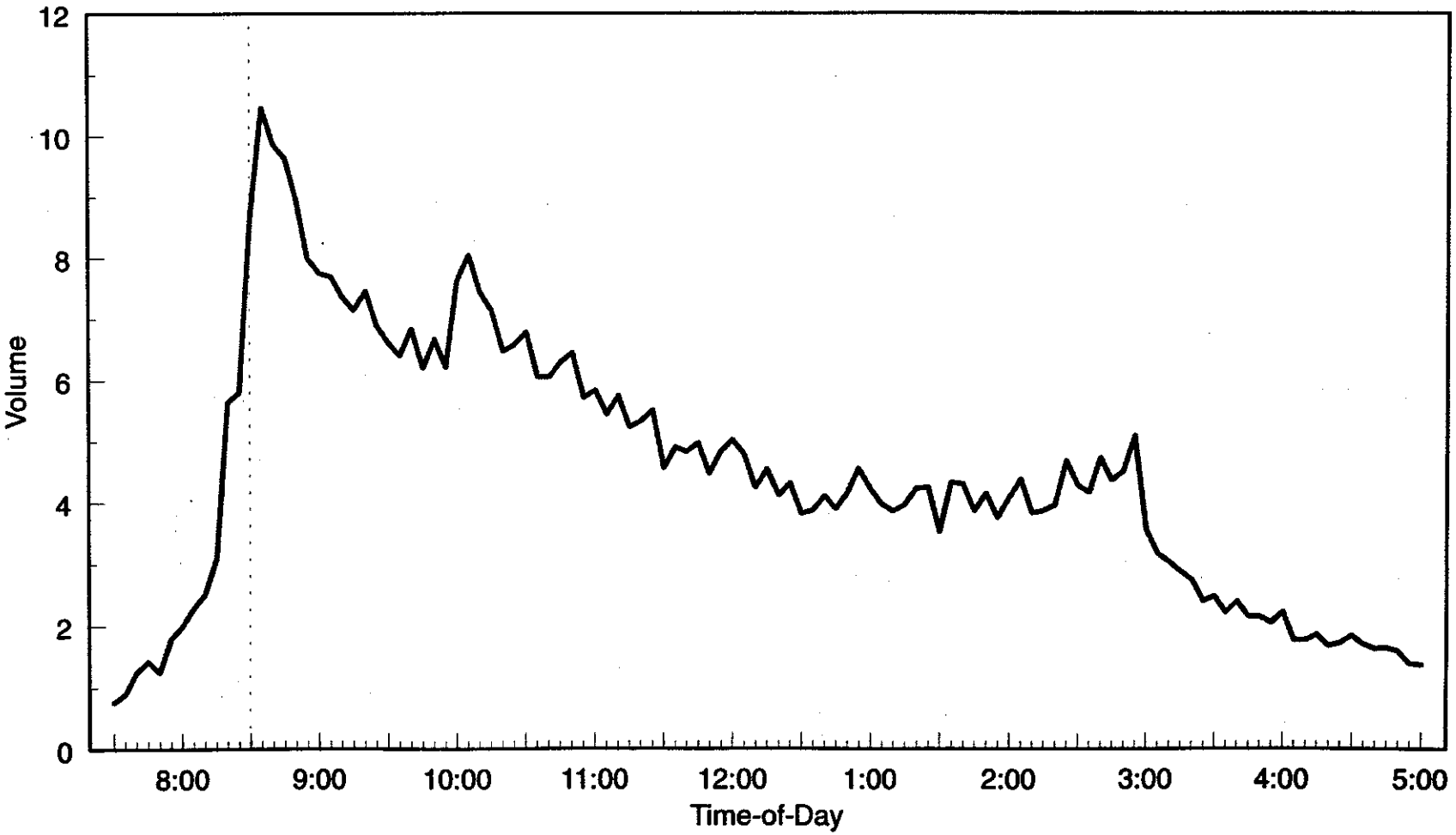


Figure 2B

Intraday Trading Volume on Announcement and Nonannouncement Days

Mean interdealer trading volume for the five-year treasury note for days with at least one of the nineteen announcements listed in Table I and days with none of these announcements. Trading volume is reported in tens of millions of U.S. dollars, the period of analysis is August 23, 1993 - August 19, 1994, and times shown are interval start times (ET).

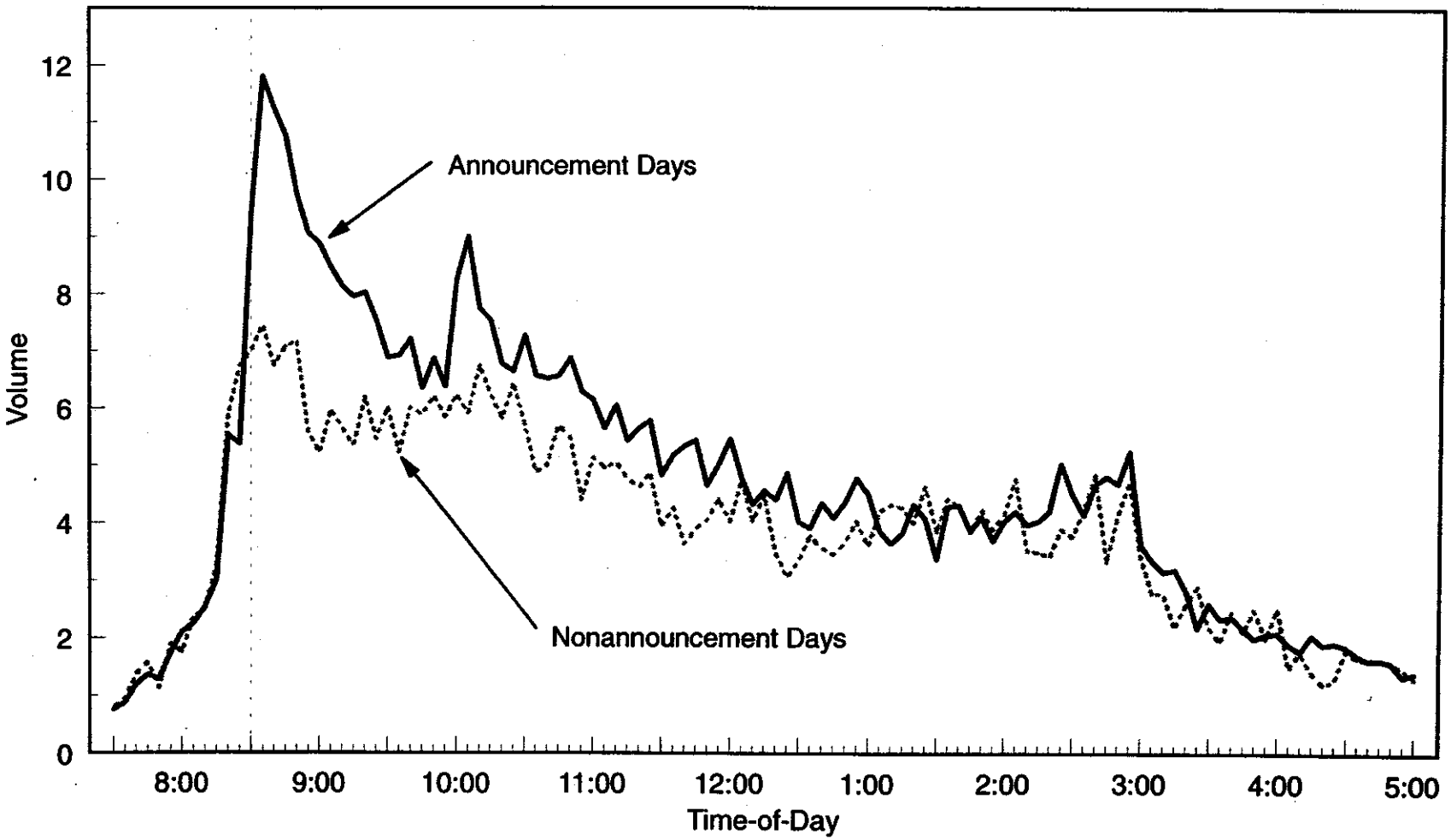


Figure 3B

Intraday Bid-Ask Spread on Announcement and Nonannouncement Days

Mean interdealer bid-ask spread for the five-year treasury note for days with at least one of our nineteen announcements listed in Table I and days with none of these announcements. The spread is measured in hundredths of one percent, the period of analysis is August 23, 1993 - August 19, 1994, and times shown are interval start times (ET).

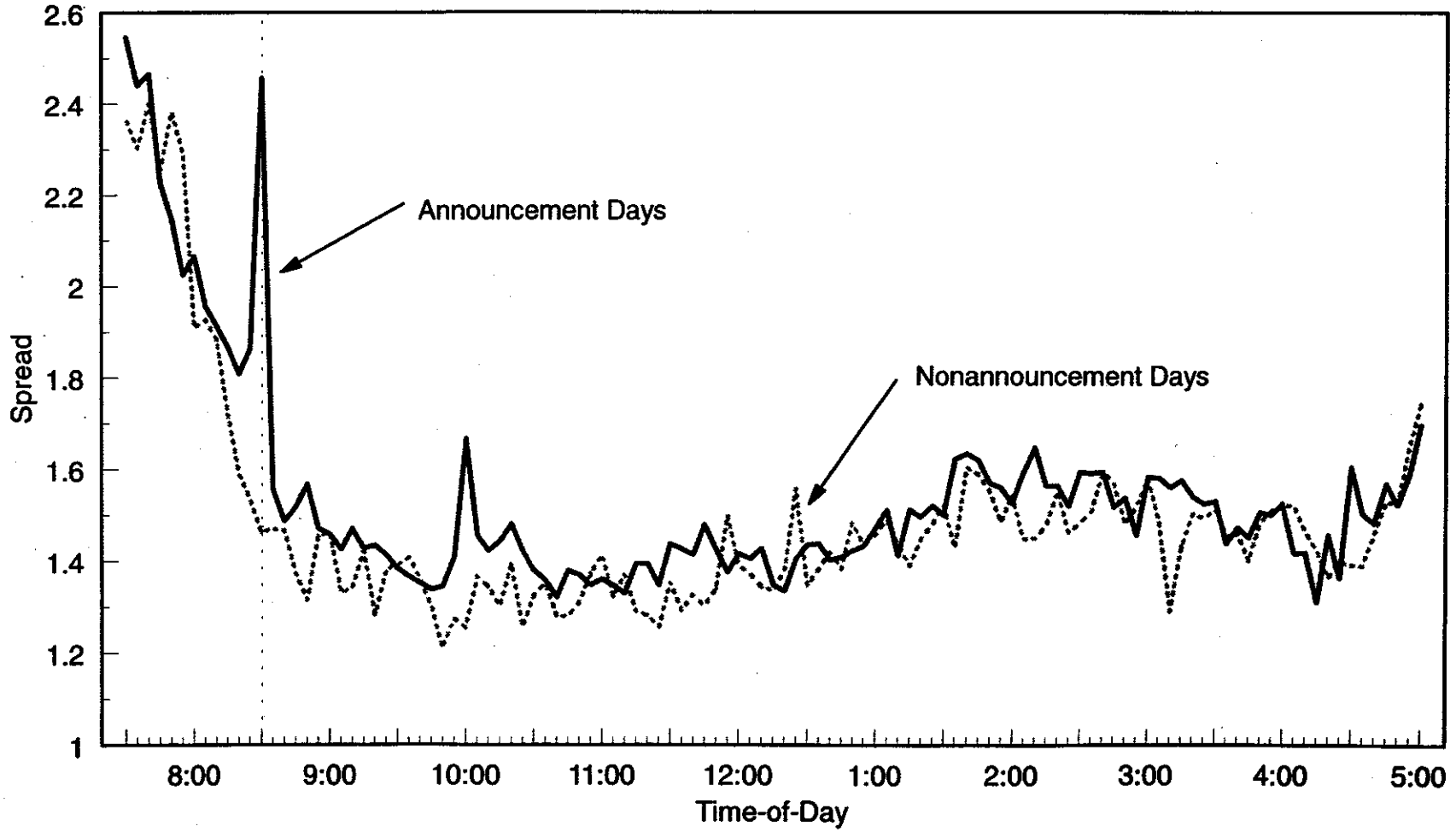


Figure 3A

Intraday Bid-Ask Spread for the Five-Year Treasury Note

Mean interdealer bid-ask spread by five-minute interval from August 23, 1993 - August 19, 1994. The spread is measured in hundredths of one percent and times shown are interval start times (ET).

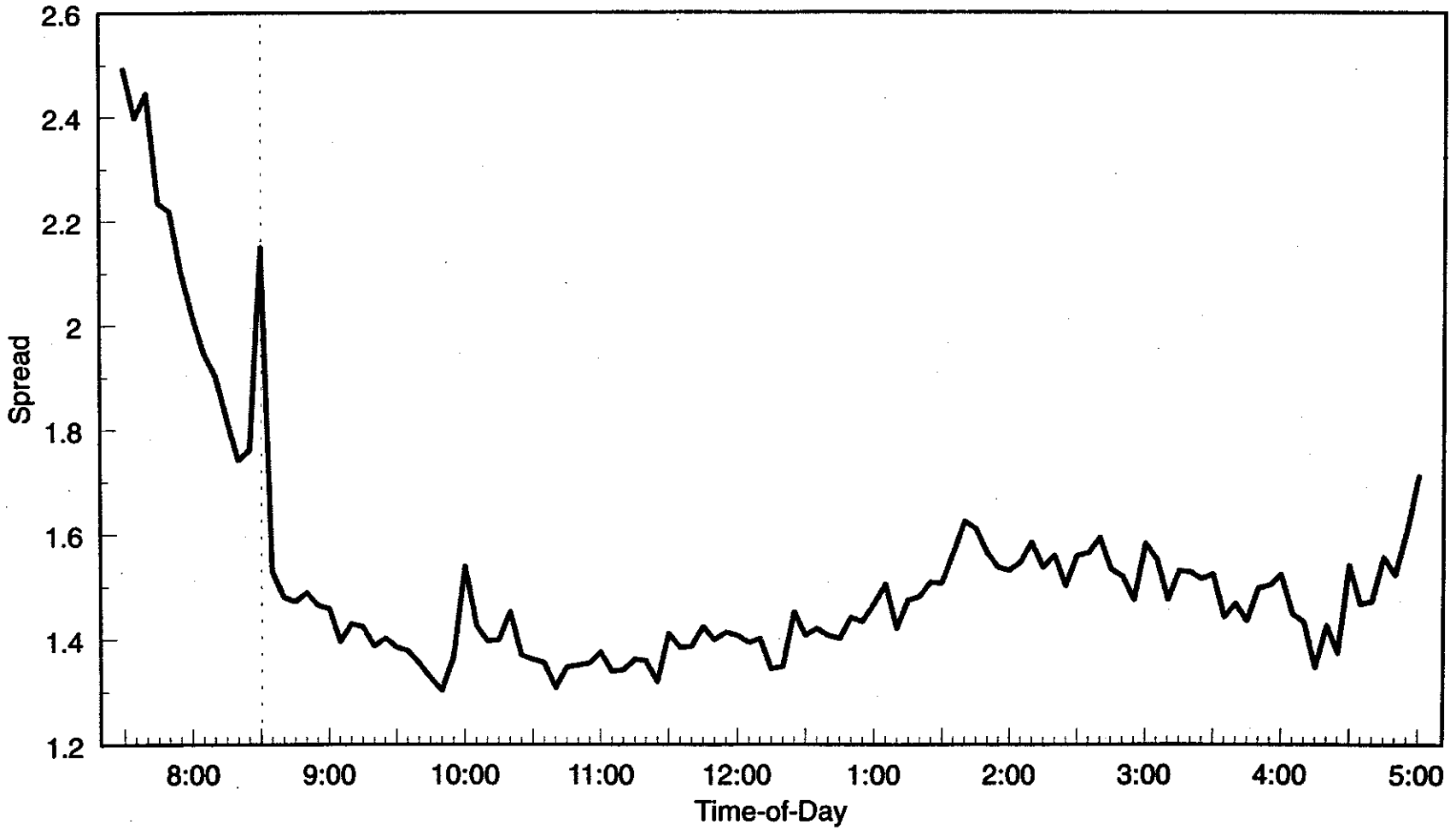


Figure 4A

Persistence of Price Volatility After Major 8:30 AM Announcements

Ratio of the standard deviation of log price changes on major 8:30 AM announcement days to nonannouncement days for the five-year treasury note. Ratios significant at the five percent level or better are indicated by diamonds. The period of analysis is August 23, 1993 - August 19, 1994 and times shown are interval start times (ET).

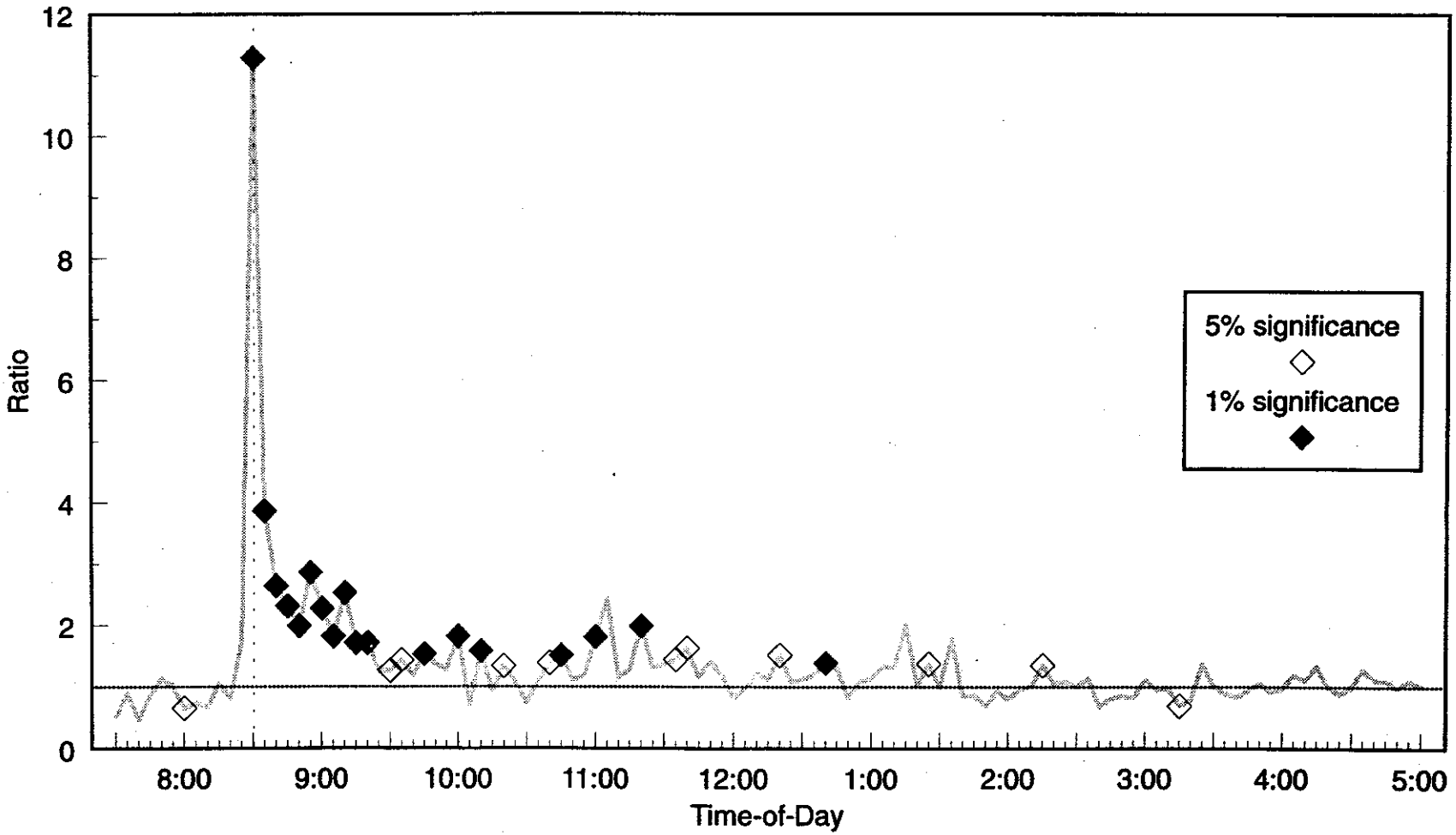


Figure 4B

Persistence of Trading Volume After Major 8:30 AM Announcements

Difference in mean interdealer trading volume between major 8:30 AM announcement days and nonannouncement days for the five-year treasury note. Differences significant at the five percent level or better are indicated by diamonds. The volume difference is reported in tens of millions of U.S. dollars, the period of analysis is August 23, 1993 - August 19, 1994, and times shown are interval start times (ET).

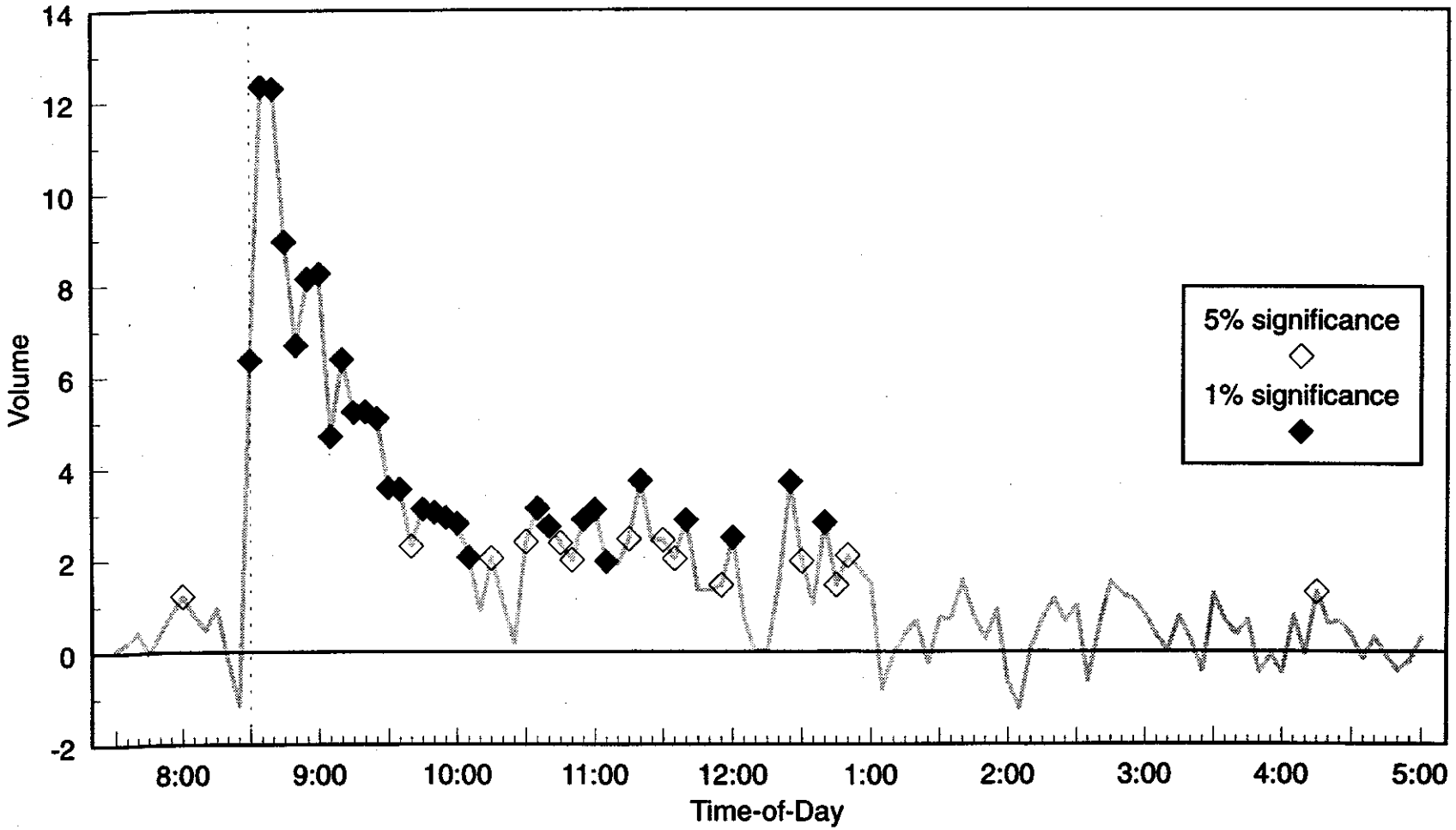


Figure 4C

Persistence of Bid-Ask Spread After Major 8:30 AM Announcements

Difference in mean interdealer bid-ask spread between major 8:30 AM announcement days and nonannouncement days for the five-year treasury note. Differences significant at the five percent level or better are indicated by diamonds. The spread difference is measured in hundredths of one percent, the period of analysis is August 23, 1993 - August 19, 1994, and times shown are interval start times (ET).

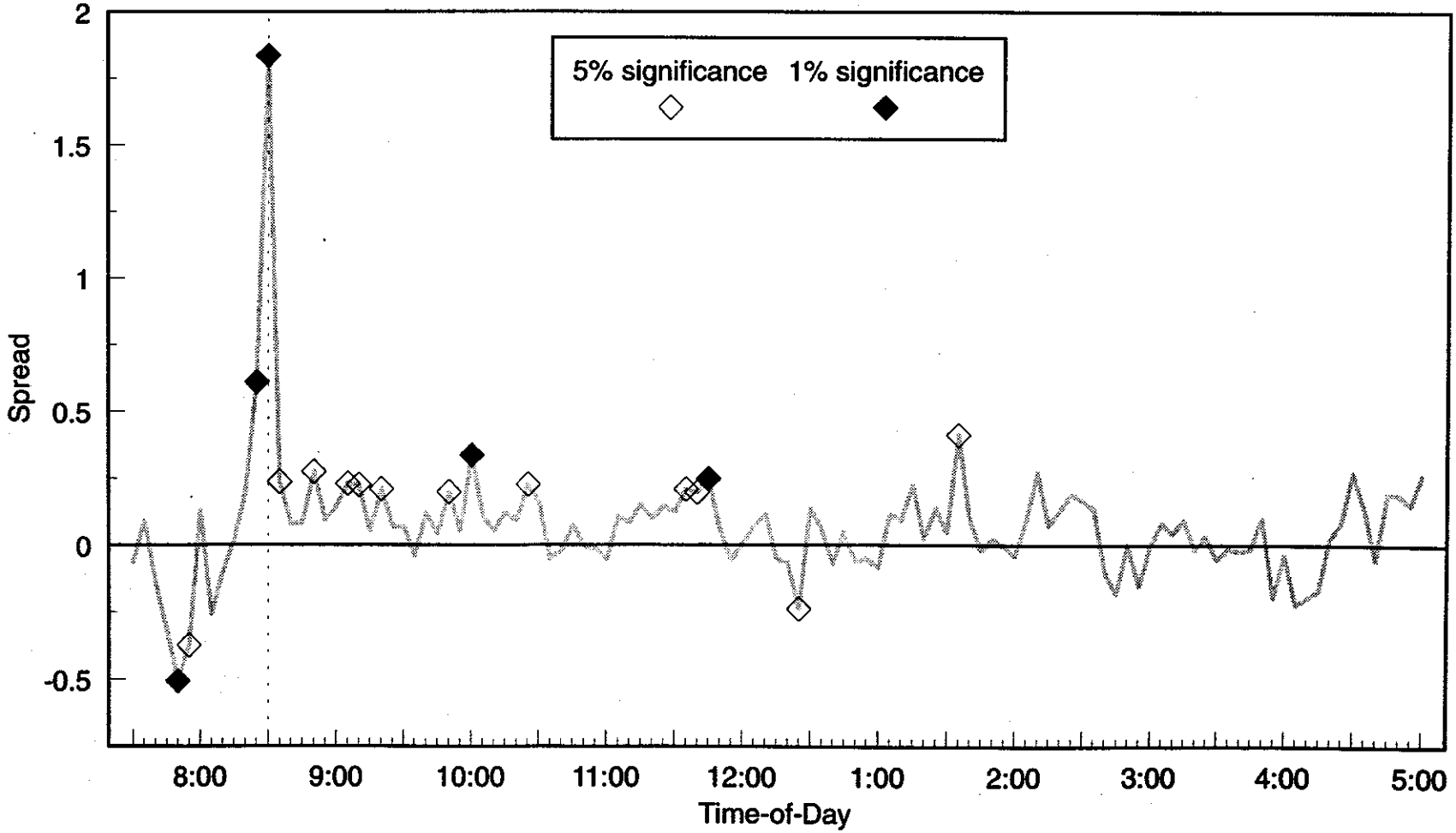


Figure 5

Market Response to August 5, 1994 Employment Report

Mean interdealer bids, asks, and transaction prices, and interdealer trading volume for the five-year treasury note by one-minute interval between 8:00 AM and 10:00 AM on August 5, 1994. Trading volume is reported in tens of millions of U.S. dollars and times shown are interval start times (ET).

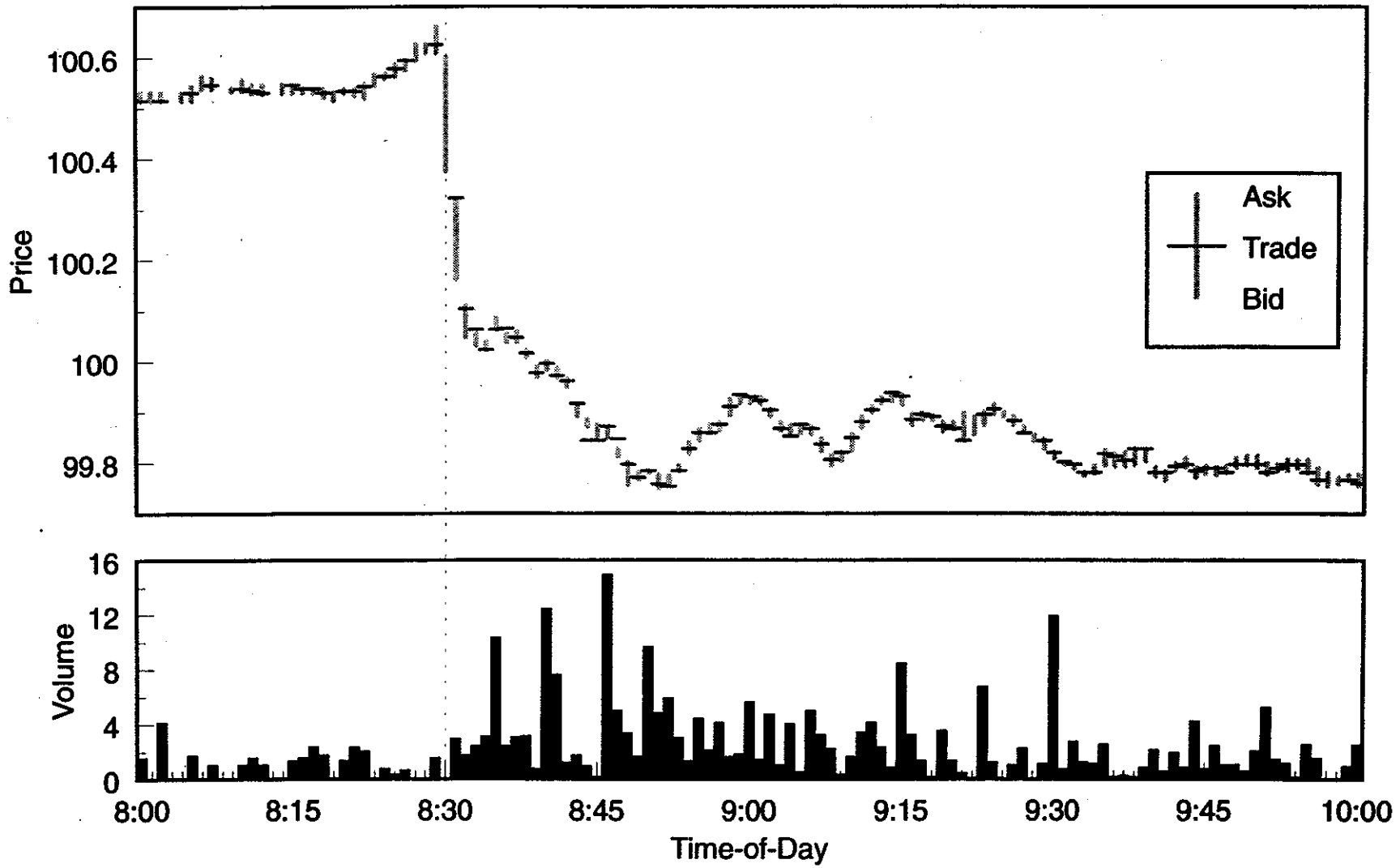
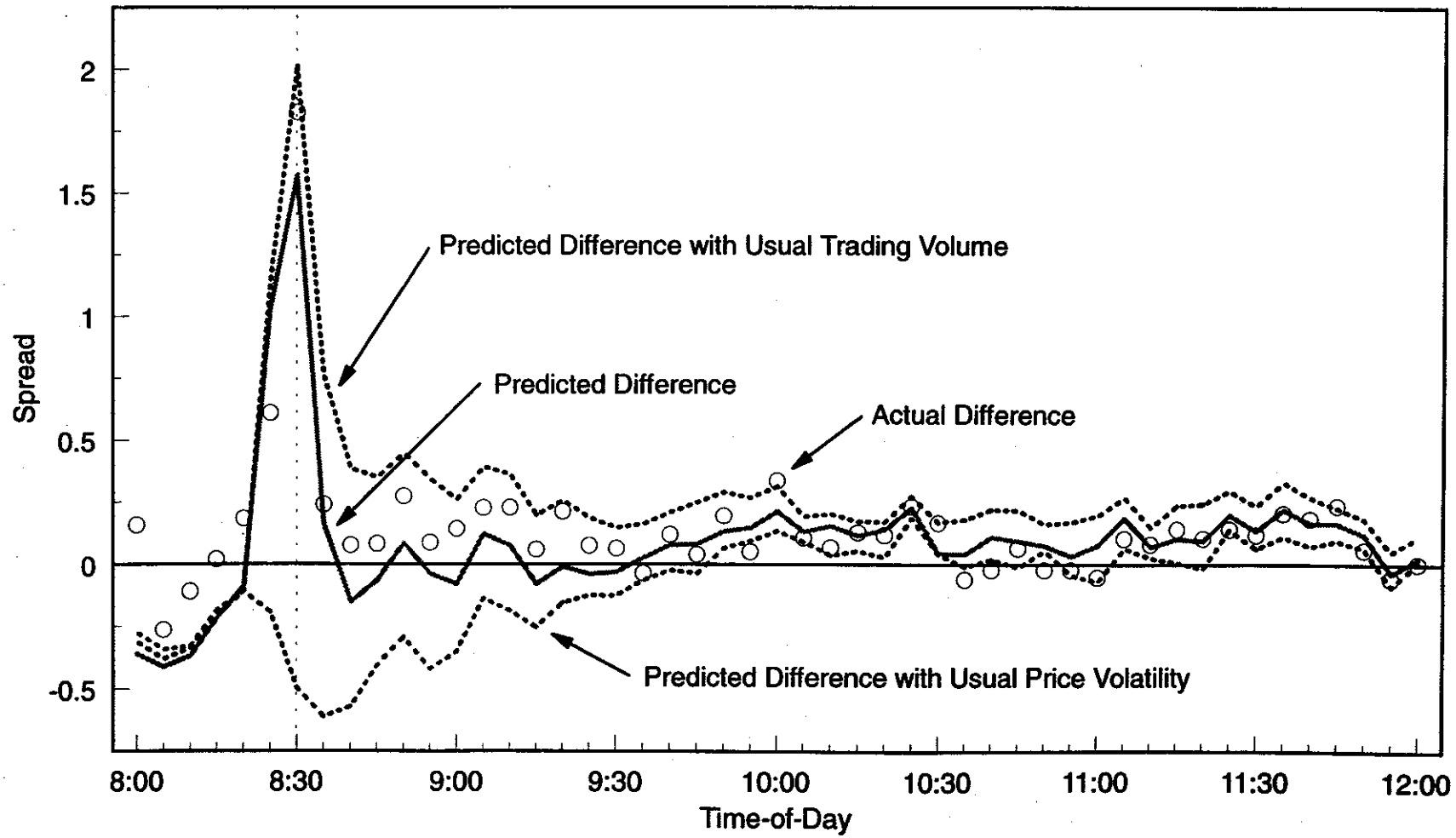


Figure 6

Bid-Ask Spread After Major 8:30 AM Announcements

Actual and predicted differences in mean interdealer bid-ask spread between major 8:30 AM announcement days and nonannouncement days for the five-year treasury note. The spread is measured in hundredths of one percent, the period of analysis is August 23, 1993 - August 19, 1994, and times shown are interval start times (ET).



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