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Abstract

We analyze how price discovery in the inter-dealer market for U.S. Treasury securities differs between stressful times and normal periods. Using tick-by-tick data on inter-dealer transactions in the on-the-run two-year, five-year and 10-year Treasury notes, we find that the impact of trades on prices tends to become significantly stronger on stressful days. This effect remains after accounting for the faster trading, wider spreads, and shallower depth observed on stressful days.

Keywords: price discovery, liquidity, depth, market makers, Treasury market

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But "liquidity" is a straw man. Whenever markets plunge, investors are stunned to find that there are not enough buyers to go around.

-- Lowenstein (2000), p. 42

1. Introduction

How different is price discovery in a market under stress? The U.S. Treasury market in autumn 1998 was such a market. At that time, a hedge fund, Long-Term Capital Management (LTCM), faced untenably heavy losses in Treasury securities, while some of its important counterparties in other markets also happened to be dealers in the Treasury market. As a consequence, the market experienced three unusual features. First, trading in Treasury securities tended to be intense, with durations between transactions shorter than usual. Second, market depth on both the buy and sell sides fell significantly. Third, bid-ask spreads widened noticeably. It therefore appears that market makers became reluctant to take risks. The specific question we ask is whether the relationship between trading flows and prices is qualitatively and quantitatively different in such a market.

In the market microstructure literature, order flow affects prices because it conveys private information regarding the value of the underlying asset. In Glosten and Milgrom (1985), for example, market makers set a positive bid-ask spread as compensation for trades made with counterparties with superior information. As a sequence of sell orders arrive, market makers lower bid prices, incorporating the probability that the order flow implies that better-informed investors believe the previous price was too high. In a general empirical framework, Hasbrouck (1991) documents the positive relationship between order flow and price changes using a sample of 80 NYSE and AMEX stocks.

The literature has since been extended to determine *when* order flow is expected to have the greatest impact on prices. In particular, times of intense trading activity have been distinguished from times of slow trading. In Admati and Pfleiderer (1988), discretionary liquidity traders try to avoid losing money to the better informed by clustering their trading at around the same time. Thus, the observation of multiple transactions occurring together suggests the presence of predominantly uninformed traders. Order flow would then not be expected to have a strong impact on prices. Contrast this intuition with that modeled by Easley and O'Hara (1992). In their model, they allow for the possibility that no new information exists. As a result, an increase in trading activity indicates that information has arrived, and therefore, order flow is more informative when transactions are occurring rapidly.[1] In a dynamic order-driven market, Foucault, Kadan and Kandel (2005) distinguish between patient and impatient traders and show that when waiting costs are large -- presumably when there is new information to exploit -- traders will tend to be more aggressive in adjusting the prices in their limit orders.

The empirical evidence on when order flow is important suggests that it depends on the market being considered. In foreign exchange markets, Lyons (1996) documents that trades are less informative when they occur when transaction intensity is high, a finding consistent with the theoretical prediction of Admati and Pfleiderer (1988). Lyons describes the phenomenon as "hot-

[1] Diamond and Verrecchia (1987) model the interaction of short-sale restrictions on the information content of order flow. Because of these constraints, a period of slow trading is likely to signal bad news. Further, these constraints impart a delay in the reaction of prices to new information, especially to bad news.

potato" trading whereby foreign exchange dealers rapidly and repeatedly lay off unwanted inventory in response to an initial potentially informed trade. By contrast, in equity markets, Dufour and Engle (2000) explicitly incorporate the role of inter-transaction time in the empirical framework of Hasbrouck (1991) and find that when equity markets are most active, i.e., inter-transaction times are short, the impact of order flow on prices is enhanced. Thus, the empirical literature has found opposite relationships between inter-transaction times and the price impact of trading depending on the market being examined.[2]

Our paper contributes in many ways to the understanding of when order flow exerts a stronger influence on prices. To begin, we expand the model of Dufour and Engle (2000) to test whether the relationship between trading and returns in on-the-run US Treasury securities differs when those markets are under stress. After controlling for the differences in the rate of trade arrival, we still find a noticeably higher price impact of a trade on stressful days. Having proposed several alternative methods for identifying stressful days, we document that such days generally witness more rapid trading, wider bid-ask spreads, and lower posted depth. Thus, to further explore the result that stress is associated with greater price impact (lower liquidity), we expand our analysis to explicitly consider the role that spreads and depth play in the price discovery process for US Treasury securities. After controlling for inter-transaction time, spreads, and depth, we are left with the finding that trades continue to move prices more on stressful days. Further, we estimate the fraction of the stress-related price impact that the readily

[2] For the U.S. Treasury market, Brandt and Kavajecz (2004) find that "overflow" affects prices especially when liquidity is low. However, they do not specifically analyze the effect of inter-transaction times.

observable measures of liquidity can explain and find it to be quite small relative to the thusfar unexplained decline in liquidity that occurs on stressful days. [3]

The remainder of the paper is as follows. Because microstructure analysis of US Treasury markets is relatively uncommon, we devote Section 2 to explain why private information can be expected to play a large role in the price discovery process of a security ultimately valued according to beliefs about the macroeconomy and for which there is frequent and public information. We further provide suggestive evidence that prices in US Treasury markets in 1998 were particularly more susceptible to private, rather than public information. Section 3 discusses the key sources of private information in US Treasury markets during 1998 and suggest why these events may have affected the relationship between trading and prices in the Treasury market. Section 4 develops four different methods of identifying days that might have been particularly stressful for Treasury dealers. Section 5 describes the data used in the study and present summary statistics to describe the nature of the stress periods in the market. In particular, we document that regardless of which of our four stress-identification methods used, stressful days in US Treasury markets during 1998 were associated with (1) faster trading, (2) wider bid-ask spreads, and (3) shallower depth. Section 6 estimates an extension of the Dufour and Engle (2000) model on data on the 2-, 5-, and 10-year Treasury note and finds that trades move prices by much more on days we previously identified as stressful. Section 7 extends the analysis further to control for changing spreads and depth. We document that changes in trading

[3] Goldstein and Kavajecz (2004) analyze liquidity provision in equity markets by limit order traders during and near the time of the steep equity market decline in October 1997. They find that liquidity, as measured by the depth of the limit order book, declined precipitously on the day after the steep market decline. Their study, however, was focused on an analysis of the impact of market-wide circuit breakers rather than on the price impact of trading during a crisis. Further, their analysis focused only on equity markets.

frequency, spreads, and depth explain very little of the decline in market liquidity we find on stressful days. Section 8 concludes.

2. Public versus private information in Treasury market price discovery

The announcement literature would suggest that public rather than private information drives price movements in US Treasury markets. Indeed it has been documented that macroeconomic announcements are often the source of the largest moves in Treasury security prices. For example, Furfine (2001) reports that of the 25 largest five-minute price moves in the on-the-run 5-year Treasury note during 1999, 19 were associated with a macroeconomic announcement, 4 with an announced change in the Federal Reserve's target federal funds rate, and 2 were coincident with testimony delivered by Federal Reserve Board Chairman Greenspan. In a study of Treasury markets from the mid-1990s, Fleming and Remolona (1999a) report, too, that public news releases explain virtually all of the largest high-frequency price movements in Treasury markets. Fleming and Remolona (1999b) further indicate that prices generally adjust rapidly in the wake of an announcement without a large increase in trading. Thus, previous literature documents that at very high frequencies, public information is the source of the larges moves of US Treasury prices, and that these movements occur without a large amount of trading.

Although news releases on occasion move prices in a matter of minutes, Treasury prices move a lot even when such public announcements are absent. In the minutes and hours after a news release, however, prices of Treasury securities are influenced by trading for the same reasons assumed in equity and other markets. For instance, although there may be a public news release of the monthly employment report, Treasury market participants will differ (at a minimum) according to (a) their beliefs with regard to the implication of the news for interest rates and (b) the degree to which their current holdings of a particular security should be altered in light of the news. As an illustration of both public and private sources of information influencing Treasury market prices, Figure 1 graphs the price and trading volume of the on-the-run 5-year Treasury Note on December 4, 1998. At 8:30 that morning, a surprisingly positive employment report was announced. As the figure reports, Treasury prices fell quickly in the first five minutes following the announcement. However, throughout the remainder of the day, heavy trading pushed prices up and then back down, without the release of any new significant public information. This suggests that although public information has a large impact on Treasury prices over very short time intervals, the general relationship between trading and pricing can still be modeled as being driven by private information.

Not only does private information have an important role in price discovery in Treasury markets in general, but the relative importance of private versus public information during the fall of 1998 appears to have been greater than was different from the periods examined by Furfine (2001) and Fleming and Remolona (1999a). First, although late 1998 witnessed its share of large and rapid price movements, these were less often associated with macroeconomic news releases. Table 1 lists the largest 25 five-minute price changes of the 5-year on-the-run Treasury Note occurring between May 1, 1998 and December 31, 1998. Of these, only *five* were associated with macroeconomic news announcements, 4 with changes in the Fed's policy rate, and 2 with statements from Alan Greenspan. As Table 1 illustrates, the majority of large price changes in late 1998 were not associated with an obvious, direct piece of macroeconomic news. In this way, private interpretation by market participants of events such as a weakening dollar, political anxiety, and the Russian economy played a larger role in price movements than is typically seen.

3. Private information, Long-Term Capital Management, and Treasury markets in 1998

The importance of private information in the U.S. Treasury market should come as no surprise. It is a multiple-dealer market in which, as in the classic model by Ho and Stoll (1980), dealers face inventory risk in competing against one another. Unlike the model, however, U.S. Treasury dealers also take highly leveraged proprietary positions and thus must rely on private information.

Among the most significant sources of private information in Treasury markets during late 1998 related to the hedge fund Long-Term Capital Management (LTCM). This fund had taken large positions in Treasury securities and Treasury related securities like swaps. As LTCM became financially troubled in August 1998, market participants remained uncertain regarding the size of LTCM's positions, the hedge fund's likely response to its difficulty, and the trading response of other market participants that had taken similarly losing bets in financial markets. Developments with LTCM were likely to result in less risk-taking by US Treasury dealers, consistent with the empirical evidence we will provide.

By late August 1998, the partners of LTCM knew they were in trouble. Among other losing positions, the hedge fund held long positions in swaps and short positions in on-the-run Treasury securities.[4] When spreads between 10-year swap yields and Treasury yields widened by 10 basis points on 21 August, the hedge fund faced untenably large losses. That Monday, the partners started seeking new investors, while the spread continued to widen. The next day, the 10-year spread reached 84 basis points, the widest spread the fund had seen since it started

[4] See the excellent accounts by the Committee on the Global Financial System (1999) and Lowenstein (2000). For more on LTCM's trading strategies, see Edwards (1999), President's Working Group on Financial Markets (1999) and Jorion (2000).

operating. The spread had increased 21 basis points over just three trading days. As volatility in this spread continued in September, the fund failed to raise enough funds to cover its losses. Finally, on 23 September, the fund's major creditors agreed to recapitalize it. Losses continued into October as swap spreads widened further, reaching 93 basis points on 5 October, the day of the single greatest rise in spreads. On 14 October, the 10-year swap spread reached its peak at 97 basis points.

There are good reasons to believe the troubles of LTCM affected price and trading behavior in the U.S. Treasury market. The Johnson Report of the Committee on the Global Financial System (hereafter, CGFS (1999)) points to three ways in which market strains were exacerbated following the fund's admission in early September of large losses. First, market participants traded on anticipation that LTCM would have to close out its positions. Second, dealers apparently anticipated counterparty losses from their positions with LTCM and thus saw their own capacity to absorb risk to be lower than before. And third, dealers began to harbor doubts about the creditworthiness of other firms that had emulated LTCM's strategies, and thus perceived a rise in the counterparty risk of dealing with these other firms.

Why would the knowledge that LTCM needed to close out its positions alter price and trading behavior? At the very least, dealers may try to trade ahead of LTCM, a strategy described as “predatory trading” by Brunnermeier and Pedersen (2005). Indeed Cai (2002) finds evidence of such front-running behavior. More importantly, LTCM’s positions were thought to be very large, but there was uncertainty about precisely how large these were and what LTCM’s unwinding strategy would be. Gennotte and Leland (1990) model a similar situation in October 1987, when market participants knew that dynamic hedging strategies required program traders to sell equities but were unsure about the size of the traders’ positions. The uncertainty about order flows, even what are supposed to be just liquidity flows, gave prices an unusually critical role in the formation of expectations, a situation that ultimately led to a sudden withdrawal of market making and to the crash of 19 October 1987. In the case of the LTCM episode, CGFS (1999) and Furfine and Remolona (2002) document that various spreads widened, including spreads between swaps and Treasury securities and between off-the-run and on-the-run Treasuries. Chordia, Sarkar, and Subrahmanyam (2005) also note wider bid-ask spreads in Treasury markets during the last half of 1998 and therefore add dummy variables to distinguish this period in their time series analysis of comovement of stock and bond liquidity.

There have been a few other studies based on the events surrounding LTCM. Kho, Lee and Stulz (2000) document that the equity prices of the firms that would ultimately participate in the bailout of LTCM declined on the days surrounding 2 September, when it first became public that LTCM had suffered large losses in August. The magnitude of the decline even exceeded similarly calculated declines around the time of the previous financial crises in Mexico, Korea, Russia, or Brazil. Furfine (2006) finds that these same institutions were still able to maintain their levels of overnight unsecured borrowing during the crisis period. Combined with the findings of Kho, Lee and Stulz, Furfine's finding suggests that although the LTCM episode had a dramatic impact on bank equity valuations, it did not threaten any major bank's solvency. Furfine further finds that these same financial institutions dramatically began to curtail risk-taking in the days leading up to LTCM's resolution in ways consistent with reductions in short-term trading activities.

All these studies suggest at least two reasons why the Treasury market on certain days in autumn 1998 may be considered to have been fundamentally different from other days. First, market depth fell noticeably. Second, most dealers may be expected to have become more reluctant to make markets during this period. They were unsure about the size of LTCM's positions and those of the fund's emulators. Many of the dealers had already incurred trading losses in August, especially from exposures to Russia.[5] Some also happened to be counterparties of LTCM and were concerned about the possibility of the hedge fund's default. Thus, dealers may be expected to have withdrawn from risk taking, perhaps by increasing their bid-ask spreads and by reducing the quantity they were willing to trade at posted prices (their posted depth).[6] Note that there is no clear implication that trading activity should become more intense during this period, but this is something we will find in the data.

4. Identifying stress days in 1998

For the purposes of our analysis of day-to-day stress, it is important that we try to identify stress days independently of what is going on in the US Treasury market itself. This is to avoid assuming what we are trying to show, which is that the market behaves differently during these days. Narratives of the LTCM episode, for example, tend to focus on days when the spread of swap yields over Treasury yields widened sharply. Using such spread movements as a criterion, however, would mean choosing some days in which the Treasury yield fell, making it somewhat difficult to disentangle our results from our choice of stress days. Since there is no established alternative way of identifying these days, we propose four definitions. Table 2 reports the days identified under the various definitions. The first definition is based on significant events identified by two narratives of the LTCM episode. The others are based on information from markets other than the Treasury market that would indicate reluctance by Treasury dealers to

[5] See President's Working Group on Financial Markets (1999).

[6] In a theoretical model of convergence trading, Xiong (2001) shows how capital losses would cause convergence traders, such as LTCM and some dealers, to reduce their risk-bearing capacity.

perform their market-making role. These definitions give us different numbers of stress days, ranging from four days to 70 days. We undertake the analysis for each of the four definitions.

1. *Stress days I:* For our first definition of stress days, we rely on events identified by CGFS (1999) and Lowenstein (2000) as being significant for the LTCM crisis. As shown in Table 2, these events give us 21 days, starting on July 6, when Salomon began to wind down its bond arbitrage operation, and ending on October 10 and 11, when Ellington Capital Management auctioned $1.5 billion of mortgage securities. This definition does include two days (September 10 and October 9) that refer to sharp movements in on-the-run Treasury yields and one day (September 12) that is about a widening of the swap spread, which is presumably calculated with the on-the-run Treasury yield.
2. *Stress days II:* For our second definition, we rely on information from the stock market. Kho, Lee and Stulz (2000) identify four days in which the stocks of four banks exposed to LTCM significantly underperformed the stocks of non-exposed banks. These exposed banks were also dealers in the Treasury market. While news about LTCM's losses became public on September 2, Kho, Lee and Stulz find that the four banks had negative returns starting on the day before and these losses continued for the next two days. As shown in Table 2, during the three days in question, the banks suffered abnormal returns of -14.2% relative to non-exposed banks. On September 24 again, these banks' stocks underperformed by 2.56%, after market participants learned how much each bank would contribute to LTCM's recapitalization. This definition gives us four stress days.
3. *Stress days III:* For our third definition, we rely on information from the corporate bond market. Rather than use corporate spreads directly, we rely on estimates by Reinhart and Sack (2002). They use weekly interest rate data to decompose the spread of 10-year double-

A corporate bonds over on-the-run Treasury securities into various premia associated with a credit risk factor, a liquidity factor and an idiosyncratic Treasury factor. The advantage of using their estimates is that their decomposition is designed to isolate their estimates of credit risk premia from any influence of the Treasury market, allowing us to consider their estimates to be exogenous to the market we are analyzing. The corporate bond yields used also happen to be the appropriate ones, because most bank dealers in the Treasury market have double-A credit ratings. For 14 weeks during our sample period, shown in Table 2, the estimated credit risk premium exceeds 60 basis points and is markedly higher than during any other week. Using these weeks for our stress days gives us a continuous period of 57 trading days.

4. *Stress days IV:* For our fourth definition, we rely on information from the swaps market. We identify the ten days in our sample period during which the five-year swap yield rose the most. As shown in Table 2, each of these ten days saw swap yields rise by at least 7 basis points. Since LTCM had long positions in swaps, sharp yield increases would have added to its counterparties' concerns that it might default. If, as reported, a number of dealers had emulated LTCM's swap positions, they themselves would have faced heavy losses from such increases in swap yields.

The four definitions differ significantly in the specific stress days they identify. The most apparent differences are in the number of days they each provide. The Johnson-Lowenstein events (stress days I) provide 21 days, the Kho-Lee-Stulz bank returns (stress days II) four days, the Reinhart-Sack credit spreads (stress days III) 57 days and the swap yield increases (stress days IV) 10 days. There are also systematic differences in where in the calendar period they tend to select stress days. The 20 days of stress days I are spread largely across August and

September, the four days of stress days II are all in September, the 57 days of stress days III cover most of the trading days from September through November, and the 10 days of stress days IV are found mostly in September through December.

5. High-frequency data from the inter-dealer Treasury market

Our U.S. Treasury data cover eight months of tick-by-tick quotes and transactions in the inter-dealer market. The source of the data is GovPX, which consolidates data from five of six inter-dealer brokers, accounting for perhaps half of all transactions in the market. The data include the best bid and offer quotes for each security, the depths for both ask and bid quotes, the price and size of each trade, and an indicator for whether the trade was initiated by a buyer or a seller. Our analysis uses data on the 2-year on-the-run Treasury notes, 5-year on-the-run Treasury notes and 10-year on-the-run Treasury notes.[7]

Our data sample runs from May 1, 1998 to December 31, 1998. To avoid times of very slow trading activity, we exclude trades occurring outside of US business hours, with business hours being defined, as in Fleming and Remolona (1999a and 1999b), as 7:30 AM to 5:00 PM ET. We further drop the data for 8 days that are all associated with an extended market break involving a major US holiday. This criterion excludes one day that otherwise would have been considered stressful, October 9, because of its proximity to the Columbus Day weekend. Because we are interested in the typical relationship between inter-transaction time and market dynamics, we would like to avoid the possibility of atypically slow trading days influencing our results. We also drop observations on 3 days where there were problems with the GovPX data for at least part of the day. Finally, to avoid confounding the data with large overnight price changes, we follow Dufour and Engle and drop observations near the beginning and end of each business day. After these adjustments to the data, we are left with 67,428, observations for the 2-year note, 103,377 observations for the 5-year note, and 83,999 observations for the 10-year note.

As shown in Table 3, our 8 months of data covers 156 trading days. The three different securities have different typical levels of trading (as captured by GovPX), with the 2-year note having the most value traded, but the 5-year note having the highest number of trades. For all three securities, buyer initiated transactions are more common than those initiated by a seller. This is consistent with the role of the primary securities dealers. These market participants buy new Treasury securities at auction and then gradually liquidate their position by the next auction. In combination with their commitment to make markets in these securities, major dealers would gradually reduce their position in on-the-run issues through the posting of limit orders, which ultimately will lead to buyer-initiated trades. All three securities are relatively actively traded, with a transaction occurring approximately once a minute. Depths and spreads are also reported in Table 3 to give a basis of comparison to interpret the magnitude of changes that occurred on particularly stressful days. For example, the average posted depth was just over $17 million for the 2-year note.

Our empirical analysis in the following sections will be an attempt to quantify the degree to which stress affects the price discovery process in Treasury markets. These markets are where LTCM held losing positions. As mentioned above, LTCM held short positions in on-the-run Treasury securities and long positions in swaps. Some dealers in the market had emulated LTCM's strategies and thus held similar positions. To unwind these positions, LTCM and its emulators would have had to buy Treasury securities, and many market participants seem to have

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[7] The on-the-run security is the most recently issued security of a given original maturity. This is the security (of a

known this. Some of the same dealers were also LTCM's counterparties in the swap contracts and were thus exposed to risk that LTCM would default. The data allow us to examine the dynamics of prices and trade flows for on-the-run Treasury securities under these conditions.

Before turning to a more formal analysis, we provide some indicative evidence to suggest changes that occurred in the Treasury market on stressful days. To do so, we first converted the tick-by-tick data into data observed at 15-minute intervals. For instance, transactions within a given 15 minute interval were combined (e.g. depth was averaged, trading volume was totaled). We then ran a simple linear regression of various characteristics of the data (e.g. volume, depth) on intraday dummy variables (to control for intraday variation) and a single indicator for one of the four definitions of stress. The coefficients and robust standard errors on the stress coefficients are reported in Table 4. There are many features of the data apparent in this preliminary data exploration that are worth highlighting for the purposes of our subsequent price discovery analysis.

First, the number of transactions and average dollar value traded rose noticeably on stressful days. For example, the dollar value traded of the 2-year note rose between \$2.7 billion per day and \$5.2 billion per day depending on the definition of stress being considered. Although theory does not necessarily predict a positive relationship between trading volume and stress, we find this to be the case for all three securities whenever the coefficient is statistically significant (9 out of 12 times). This increase in trading activity maps directly into a reduction in the average time between trades for all three securities.

We also find evidence that market makers became more risk averse, consistent with our discussion in Section 3. For example, the average quoted depth in the market became shallower

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given original maturity) with the most active trading.

during the stressful days. In the case of the 5-year note, average bid depth fell by between $1.13 million and $3.37 million (from its average value of $9.3) on stressful days. We find that depth at both the bid and ask price generally declined on stressful days, and fell most using stress definition III (wide credit spreads). Using this measure of stress, depth in Treasury markets was roughly 40% lower on stressful days than its full-sample average.

Table 4 also documents that bid-ask spreads in the Treasury market were wider on stress days relative to the entire sample period. In general, bid-ask spreads for on-the-run Treasury notes range from 0.6 basis points for the 2-year note to 2.2 basis points for the 10-year note. Although the point estimates vary across securities and across stress definitions, we find that spreads were generally wider by roughly 30%-40% on stressful days. In sum, we can characterize Treasury markets to (1) be more active, (2) have lower posted depth, and (3) have wider spreads on stressful days.

6. A VAR representation of price discovery in the U.S. Treasury market

The results in the previous section suggest that dealers became more reluctant to make markets during stressful days of 1998. This would imply a reduction in market liquidity. In Hameed, Kang and Viswanathan (2005), a decline in the collateral value of market makers leads to a fall in liquidity. To explore this possibility more formally for the U.S. Treasury market, we estimate a price discovery model that builds upon the work of Hasbrouck (1991) and Dufour and Engle (2000). We do this in two steps. First, we simply adopt Dufour and Engle's approach of explicitly incorporating inter-transaction time into Hasbrouck's VAR model of prices and trades and calculate a benchmark for the price impact of a trade in US Treasury markets. We then expand the model to allow price impact to vary according to whether or not the day was considered stressful. In this way, we are able to determine whether price impact was changed on stressful days after controlling for the aforementioned reduction in inter-transaction time.

Our empirical model consists of two equations: one for returns (quote revisions) and one for direction of trades. We define our measure of returns, r_t, as the change in the log mid-quote price between the trade at time t and trade at $t+1$. Hence, $r_t \equiv 100(\ln q_{t+1} - \ln q_t)$. For trade direction, we use Hasbrouck's (1991) indicator variable x_t^0, which is equal to $+1$ if the trade is a take (it is initiated by the buyer) and -1 if it is a hit (seller initiated).[8] Recall that the GovPX data includes information as to whether the trade was buyer or seller initiated so there is not an issue of correctly identifying trades as there often is in studies of US equity markets.

Dufour and Engle’s (2000) model explicitly accounts for trading intensity by interacting a duration variable $\ln(T_t)$ with x_t^0, where T_t is measured as one plus the number of seconds between trades at times t and $t-1$.[9] Our benchmark equations, therefore, can be expressed as shown in equations (1) and (2).

$$r_t = \sum_{i=1}^{5} a_i^r r_{t-i} + \sum_{i=1}^{5} b_i^r r_{t-i} \ln(T_{t-i}) + \sum_{i=0}^{5} c_i^r x_{t-i}^0 + \sum_{i=0}^{5} d_i^r x_{t-i}^0 \ln(T_{t-i}) + v_{1t} \tag{1}$$

$$x_t^0 = \sum_{i=1}^{5} a_i^x r_{t-i} + \sum_{i=1}^{5} b_i^x r_{t-i} \ln(T_{t-i}) + \sum_{i=1}^{5} c_i^x x_{t-i}^0 + \sum_{i=1}^{5} d_i^x x_{t-i}^0 \ln(T_{t-i}) + v_{2t} \tag{2}$$

Note that our equations differ from Dufour and Engle's in that we add lags of $r_t \ln(T_t)$ to both equations to account for an interaction between quote revisions and durations in addition to the interaction between trading and durations. We follow Dufour and Engle (2000) and make the

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[8] Also following Hasbrouck (1991) we estimated the model replacing the trade indicator variable with a continuous variable measuring the size of the given trade. All of our empirical results were qualitatively unchanged.

[9] The data contain a few cases in which measured duration between trades is zero. To keep log values finite, we add one second to each inter-transaction time.

assumption that the lag polynomials may be truncated after the fifth lag. Also, like Dufour and Engle (2000), we identify the system by assuming that a trade at *t* affects the returns from *t* to *t+1*, but that this return can only affect trades beginning at *t+1*. This is reflected in the 0-lag terms in equation (1).

To measure the effect of stressful days arising from the risk aversion of market makers, we estimate a slightly expanded system, shown in equations (3) and (4). For these equations, we further define a dummy variable D_t^S that takes on the value of 1 if *t* occurs on one of the days we have identified as stressful and 0 otherwise. As described above, we consider four different definitions of stress days. We then add lagged interactions of this dummy variable with the trade indicator variable to our benchmark equations. In this way, we will examine whether trades affect prices differently on stressful days after controlling for the possible changes in inter-transaction time (trading intensity).

$$r_t = \sum_{i=1}^{5} a_i^r r_{t-i} + \sum_{i=1}^{5} b_i^r r_{t-i} \ln\left(T_{t-i}\right) + \sum_{i=0}^{5} c_i^r x_{t-i}^0 + \sum_{i=0}^{5} d_i^r x_{t-i}^0 \ln\left(T_{t-i}\right) + \sum_{i=0}^{5} e_i^r x_{t-i}^0 D_{t-i}^S + v_{1t} \tag{3}$$

$$x_t^0 = \sum_{i=1}^{5} a_i^x r_{t-i} + \sum_{i=1}^{5} b_i^x r_{t-i} \ln\left(T_{t-i}\right) + \sum_{i=1}^{5} c_i^x x_{t-i}^0 + \sum_{i=1}^{5} d_i^x x_{t-i}^0 \ln\left(T_{t-i}\right) + \sum_{i=1}^{5} e_i^x x_{t-i}^0 D_{t-i}^S + v_{2t} \tag{4}$$

Tables 5(a), 3(b) and 3(c) summarize our coefficient estimates from estimating equations (1)-(4) on data for the 2-year, 5-year and 10-year on-the-run Treasury notes respectively. The tables report the sum of the estimated coefficients on lagged values for each variable and the p-values for a Wald test of the significance of this sum. The first column in each table reports the results for the estimation of benchmark equations (1) and (2). The other four columns report the results for equations (3) and (4), with each column representing a different definition of stress days. The estimates for the return equations are shown in the top half of each table and the estimates for the trade-side equations are shown in the bottom half.

Our results suggest that the dynamics of the Treasury market have features in common with other markets. For example, as shown in the first row for the return equations, we find that Treasury market returns are negatively related to past returns. Furthermore, the second row indicates that the coefficient on trade sign is positive. This is the result one would expect. That is, buying should lead to a price rise and selling to a price fall. Hasbrouck (1991) and Dufour and Engle (2000) have documented these results for equity markets. We also document that both of these relationships are greater in magnitude as the maturity of the bond increases.

Our coefficient estimates on the terms interacted with inter-transaction time suggest that the above-mentioned relationships become stronger during periods of intense trading. For example, as shown in the third row, the sum of the coefficients on the lags of the interaction between returns and inter-transaction times is positive. This indicates that during periods of more intense trading (smaller inter-transaction time), current returns become even more strongly negatively related to past returns. As shown in the fourth row, the sign of the coefficients on the interaction term between inter-transaction time and the price impact of a trade is negative. This indicates that periods of more intense trading are associated with a stronger price impact of a given trade. The stronger price impact of trades during busy times is consistent with Easley and O'Hara (1992), where informed traders seem impatient to trade, perhaps because the value of their information deteriorates with time. It is also the same empirical relationship found by Dufour and Engle (2000) in their study of equity markets. Thus, periods of intense trading involve on average more trades that are perceived by market makers as informed, and therefore each individual trade has a larger influence on price.

The results for the trade-side equation suggest that there is a positive relationship between past returns and current trades. This is in contrast to the result found by Hasbrouck in equity markets. However, it supports the findings of Cohen and Shin (2001), who also analyze data from GovPX. These authors find that on busier trading days, a positive feedback mechanism appears whereby, in the very-short run, an increase in the price of a Treasury security leads to more buy-side transactions, and a decline in the price of a security leads to an increase in sell-side transactions. As shown in the second row of the bottom panels of Table 5, trades are positively related to past trades. This finding is typical in the empirical microstructure literature. It may reflect partly an effort by informed traders to break down their desired trades into smaller pieces in order to reduce the impact on prices. The relationship between past returns and subsequent trading becomes even more positively related during times of intense trading. This is the implication of the fact that the sum of the coefficients on $r_t \ln\left(T_t\right)$, the interaction of return and inter-transaction time, is negative.

To explore how stress may change the price discovery process, we report our estimates of equations (3) and (4) in the last four columns of Table 5. The coefficients on the variables discussed earlier change very little. The key new result, however, suggests that the price impact of a trade becomes stronger on stressful days, indicating a decline in market liquidity on such days. The magnitude of the effect depends on the specific on-the-run security and the definition of stress days. The relevant variable is $x_t^0 d_t^S$, which interacts a dummy variable for stress days with our signed trade variable. The sums of the estimated coefficients for this interaction variable are shown in the fifth row of Tables 5(a) to 5(c). In all specifications, the estimated coefficients are positive, and with only 2 exceptions out of 12, highly statistically significant.

To quantify the differential impact of a stressful day on the price impact of a trade, we calculate a benchmark cumulative impulse response function plotting the impact of a positive trade shock on the returns to each of the Treasury notes based on the coefficients estimated from equations (1) and (2). This response function is plotted as the solid black line in each panel of Figure 2. To estimate the impact of stress, we consider another trade shock, only this time using estimates from equations (3) and (4) and also setting the stress dummy variables equal to 1. These impulse responses are graphed as dotted lines in Figure 2. For these two impulse responses, we set the inter-transaction time equal to the mean value for the given security that was reported in Table 3. By holding inter-transaction time constant, we are estimating the marginal price impact of a stressful day, without considering that stressful days are also associated with faster trading. Thus, the dotted lines in Figure 2 understate the total difference between the price impact of a trade on a normal day and that on a stressful day. To jointly consider the impact of stress and stress-induced reduction in inter-transaction time, the solid gray line in Figure 2 plots the impulse response of returns from a trade shock when we both set the stress dummy variable equal to 1 and also reduce the presumed inter-transaction time to the level witnessed on stressful days of the given type.

As an illustrative example, the picture at the top-left corner of Figure 2 graphs the impulse response of a trade shock on prices for the 2-year note on a non-stressful day compared with a similar response to a trade occurring on a Johnson-Lowenstein day, calculated both for average inter-transaction time and Johnson-Lowenstein-day inter-transaction time. The other pictures in Figure 2 repeat this exercise for each on-the-run security and for each definition of stress. In all 12 specifications, market stress is associated with decreased liquidity (higher price impact). For example, the ultimate price impact of a trade of the 5-year note is estimated to be around 0.4 basis points on normal days. Stressful days increase the price impact of a trade significantly. For example, using the Johnson-Lowenstein identification method, the price impact of a trade of the 5-year note increases to approximately 0.7 basis points, an increase of 75%.

Across all three securities and all definitions of stress, stressful days are associated with between a 30% and 200% increase in price impact.

These calculations are hold inter-transaction time constant and therefore neglect to consider that on stressful days, trading is more rapid, which would increase a trade's price impact even further. However, in practice, the decline in average inter-transaction time has a negligible impact on the price impact of a trade. This can be seen visually by comparing the dotted line with the solid gray line, which demonstrates that the shorter inter-transaction time on stress days increases the price impact of a trade by a trivial amount.

7. Controlling for other factors

The results in section 6 indicate that market liquidity in on-the-run Treasury markets declined on stressful days in the latter part of 1998. As discussed earlier, some signs of stress were apparent in both available depth and in posted bid-ask spreads. It could be, therefore, that the higher price impact of a trade on stressful days reported in section 6 merely reflects this lower level of depth and wider spreads. In this section, we expand our empirical framework to explicitly account for both spreads and depth to see if there remain differences in the price impact of a trade on normal versus stressful days, or whether or not any differences merely manifest themselves in these observable measures of liquidity.

To control for the possible influence of declining depth, we interact the trade indicator with a variable P_t, which measures the size of the depth in the direction of the given trade. For example, P_t would be the posted depth at the ask price if $x_t^0 = 1$ and would be equal to the posted depth at the bid price if $x_t^0 = -1$. We would expect trades will have a greater impact on prices when depth is lower. We follow an analogous approach to incorporating the information contained in bid-ask spreads. We interact the trade indicator with a variable BA_t, which measures the bid-ask spread at the time of trade t.[10] Our hypothesis is that trades occurring when spreads are wide will move prices more than trades arriving when spreads are narrow. To test the influence of spreads and depth, we add lags of the depth interaction variable and the spread interaction variable to our equations (3) and (4) to see whether depth affects the relationship between trade flows and prices.

To conserve space, we do not report the coefficient estimates from this expanded empirical specification. However, the additional coefficients were of the expected sign. That is, lower depth and higher bid-ask spreads were correlated with greater price impact. We do, however, report analogous impulse response functions in Figure 3. In each panel, the solid line is the benchmark impact of a trade on returns (keeping the stress-day indicator equal to 0), estimated from the depth- and spread- expanded versions of equations (3) and (4). These solid lines are very close to those plotted in Figure 2. The dotted line is the cumulative impulse response of returns to a trade shock from the same model, only setting the stress dummy variable equal to 1. The simulations plotted by the dotted line keep the inter-transaction time, depth, and spread variables at their full-sample mean value. As Figure 3 indicates, the increase in price impact shown in the dotted line in Figure 3 is quite close to the effect reported in Figure 2. This is due to the fact that changes in spreads and depth that accompany stressful days have a negligible impact on the price impact of a trade as indicated by the close proximity of the dotted line to the solid gray line, which estimates the impact of a trade shock on a stress day and allows inter-transaction time, depth, and spreads to adjust to their stress-day average level. Thus, we conclude that the price discovery process on stressful days is different than on normal days, even after controlling

[10] Technically, this variable measures the "touch", or the difference between the best bid and best ask price. This is

for changes in inter-transaction times, spreads, and depth that typically accompany such days. In particular, the price impact of a trade is much greater.

8. Conclusions

This paper has studied the price impact of a trade in the U.S. Treasury market during the particularly turbulent period of fall 1998. The main empirical findings are as follows: Overall, the dynamics of trading in the Treasury market are much like those founds in equity markets. In particular, returns are negatively related to past returns, trades are positively related to past trades, and order flow moves prices in the expected direction. We further find that the intensity of activity in the market, as measured by the inter-transaction time, affects the liquidity of the market, as measured inversely by the price impact of a trade. Busy times, because they are times of information-based trading, witness a significant increase in the price impact of a trade.

Most significantly, we document that stressful days during the crisis period of 1998 saw a dramatic increase in the price impact of a given trade. Even after controlling for the shorter inter-transaction times, shallower depth, and wider bid-ask spreads witnessed in the market, trading during the crisis moved prices much more than trading during the more normal times of 1998. This finding is robust across securities of different maturities as well as for various definitions of stressful days.

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what GovPX reports rather than the spreads posted by any of the individual dealers.

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Table 1			
Largest Five Minute Price Changes in the 5-Year on-the-run Treasury Note: May – Dec 1998			
Date	Time	Change in price (Basis points)	Discussion in financial press
9-Oct-98	9:15	-40.78248	"Large-scale sell-off by Japanese investors"
15-Oct-98	3:15	37.29677	Fed surprise inter-meeting rate cut
15-Oct-98	3:25	31.96435	Fed surprise inter-meeting rate cut
4-Dec-98	8:30	-27.82079	Employment report
11-Sep-98	9:50	-24.20393	"Sinking dollar", "Global political anxiety"
21-Sep-98	10:20	-21.51228	Release of President Clinton's grand jury testimony
4-Nov-98	1:25	-20.49989	"Just terrible" auction of Treasury notes
5-Nov-98	1:35	20.48535	Accidental early release of employment report
27-Aug-98	11:40	19.97696	"Worries about Russia's economic and political situation"
17-Nov-98	2:35	-18.97834	Federal Reserve cuts interest rates
8-Oct-98	12:05	-18.63378	"Large-scale sell-off by international parties amid continuing plunge in the dollar"
23-Sep-98	2:15	18.131	Greenspan testimony
3-Dec-98	8:05	-17.97788	"Investors shifted funds out of bonds and into equities"
17-Jun-98	7:55	-17.59841	US and Japanese intervention to raise yen against dollar
16-Sep-98	2:10	17.18312	Greenspan testimony
11-Sep-98	10:45	-16.67172	"Sinking dollar", "Global political anxiety"
17-Nov-98	3:05	-16.64883	Federal Reserve cuts interest rates
9-Oct-98	9:20	16.63516	"Large-scale sell-off by Japanese investors"
7-Oct-98	8:10	-16.36296	"Startling tumble in the dollar"
5-Jun-98	8:30	-15.71339	Employment report
2-Oct-98	8:30	15.63955	Employment report
27-Aug-98	11:35	15.39409	"Worries about Russia's economic and political situation"
9-Oct-98	9:30	15.10118	"Large-scale sell-off by Japanese investors"
9-Oct-98	8:30	-15.00826	"Large-scale sell-off by Japanese investors"
5-Nov-98	1:15	15.00612	Accidental early release of employment report

Table 2: Four definitions of stress days

Table 2 (a): Stress days I

Johnson-Lowenstein events

Date	Event
6 July	Salomon begins to wind down its bond arbitrage operation
20 July	WSJ headline on LTCM losses
13 August	Hong Kong market falls 8%; Russia places control on the ruble
17 August	Russia declares debt moratorium
20 August	Barclays unwinds short positions in sterling swaps
21 August	Dow falls 280 points in the morning but recovers; credit and swap spreads surge; yields rise on off-the-run Treasuries
24 August	LTCM partners start seeking new investors
27 August	Hilibrand goes to Omaha to see Buffett
31 August	Dow falls; trading in bond market disappears
2 September	LTCM issues shareholders letter
4 September	WSJ headline on Lehman Brothers' losses
10 September	10-year US Treasury yield falls
11 September	Spread on 10-year sterling swap widens
12 September	Spread on 10-year US dollar swap widens
23 September	LTCM recapitalized
29 September	Federal Reserve cuts interest rate
7-8 October	Yen rises 9%
9 October	10-year US Treasury yield rises
10-11 October	Ellington Capital management auctions $1.5 billion of mortgage securities

Sources: CGFS (1999) and Lowenstein (2000).

Table 2 (continued)

Table 2(b): Stress day definition II
Days of abnormal negative stock returns to exposed banks [1]

Date	Abnormal stock return of exposed banks [p-value]
1 September	-3.943 [0.01]
2 September	-2.899 [0.05]
3 September	-7.303 [0.00]
24 September	-2.563 [0.09]

Table 2(c): Stress day definition III
Days of wide credit spreads [2]

Period	Double-A risk spread
57 trading days between September 2 and December 2	Average of 70 basis points Minimum of 60 basis points

Table 2(d): Stress day definition IV
Ten days of greatest increases in swap yields

Date	Increase in 5-year US dollar swap yield
9 October	26 basis points
6 November	19 basis points
2 November	14 basis points
5 December	9 basis points
17 June	9 basis points
14 September	9 basis points
11 May	7 basis points
8 October	7 basis points
4 December	7 basis points
24 December	7 basis points

[1] Estimates in Kho, Lee and Stulz (2000) for four exposed banks. [2] Days of unusually high double-A credit spread as calculated in Reinhart and Sack (2002).

Table 3

Summary statistics

Each entry reports the average value of the given variable across all transactions in the dataset.

	2-Year Note	5-Year Note	10-Year Note
$ volume per day	7251.65	6137.06	4359.17
of which seller initiated	3791.59	2894.87	2133.52
of which buyer initiated	3460.06	3242.19	2225.65
Transactions per day	432	663	538
of which seller initiated	202	320	261
of which buyer initiated	230	342	277
Time between trades	77.78	50.99	62.54
Depth (at the ask price)	17.07	9.63	7.28
Depth (at the bid price)	17.66	9.34	7.97
Bid-ask spread	0.006	0.012	0.022
Memo:			
Total number of transactions	67428	103377	83999
Total number of business days	156	156	156

Table 4

Treasury market differences on stressful days

Each table entry reports the coefficient on a stress-day indicator variable and its robust standard error from a regression of the given particular bond market characteristic's 15-minute value on a series of intraday dummy variables and an indicator for the various stress day definitions. Coefficients have been adjusted to represent daily values.

	Johnson-Lowenstein	Shocks to exposed banks	Wide credit spreads	Swap yield increases
		2 - Year Note		
Trading volume	3507.641	5203.474	3245.706	2699.43
($ millions)	(405.9586)	(560.4814)	(197.0175)	(566.9482)
Total number	106.2525	230.4276	201.1122	139.9041
of trades	(13.81623)	(18.68391)	(6.694494)	(18.70823)
Depth (Ask)	-4.014758	-1.872291	-7.818723	-3.865243
	(0.6696565)	(1.166104)	(0.4222576)	(0.7223706)
Depth (Bid)	-1.856229	-2.180761	-9.188922	-2.434901
	(0.9074728)	(1.345837)	(0.4742733)	(1.202763)
Bid-ask spread	0.0017286	0.0003072	0.0020009	0.0005296
	(0.0001746)	(0.0002201)	(0.0000968)	(0.000272)
		5 - Year Note		
Trading volume	1723.77	2537.23	-3.72887	208.4928
($ millions)	(262.9885)	(426.4151)	(132.777)	(315.1848)
Total number	119.9986	230.4868	121.3232	78.11793
of trades	(17.1374)	(26.8837)	(8.99704)	(21.39303)
Depth (Ask)	-0.787309	-1.105139	-4.023322	-1.608565
	(0.355251)	(0.389113)	(0.242981)	(0.357885)
Depth (Bid)	-1.133172	-1.482113	-3.374656	-1.705170
	(0.265039)	(0.379758)	(0.170358)	(0.327783)
Bid-ask spread	0.002921	0.001441	0.006803	0.003977
	(0.000419)	(0.000358)	(0.000195)	(0.000638)
		10 - Year Note		
Trading volume	676.217	1497.237	492.4652	-189.777
($ millions)	(164.8642)	(310.769)	(103.4889)	(235.4965)
Total number	45.52199	138.3421	75.55502	5.356664
of trades	(11.61827)	(18.76562)	(6.88316)	(16.56956)
Depth (Ask)	-1.245390	0.643855	-2.341885	-1.152355
	(0.215453)	(0.740217)	(0.158076)	(0.308525)
Depth (Bid)	-1.118396	0.802170	-2.094791	-1.709977
	(0.282597)	(0.911220)	(0.221183)	(0.552405)
Bid-ask spread	0.003856	-0.000519	0.009933	0.009076
	(0.000830)	(0.000677)	(0.000385)	(0.001562)

Table 5(a)

Coefficient Estimates – 2 Year Note

The numbers in this table report coefficient estimates for the VAR model

$$r_t = \sum_{i=1}^{5} a_i^r r_{t-i} + \sum_{i=1}^{5} b_i^r r_{t-i} \ln\left(T_{t-i}\right) + \sum_{i=0}^{5} c_i^r x_{t-i}^0 + \sum_{i=0}^{5} d_i^r x_{t-i}^0 \ln\left(T_{t-i}\right) + \sum_{i=0}^{5} e_i^r x_{t-i}^0 D_{t-i}^S + v_{1t}$$

$$x_t^0 = \sum_{i=1}^{5} a_i^x r_{t-i} + \sum_{i=1}^{5} b_i^x r_{t-i} \ln\left(T_{t-i}\right) + \sum_{i=1}^{5} c_i^x x_{t-i}^0 + \sum_{i=1}^{5} d_i^x x_{t-i}^0 \ln\left(T_{t-i}\right) + \sum_{i=1}^{5} e_i^x x_{t-i}^0 D_{t-i}^S + v_{2t}$$

Estimated from data for the 2-year US Treasury note, May - December 1998. The coefficient reported is the sum of the estimated coefficients and the number in parenthesis is the p-value of a Wald test for significance of this sum.

Lagged variables	Dependent variable r_t				
	Bench-mark	Johnson-Lowen-stein	exposed banks stock returns	Wide credit spreads	swap yield increase
		I	II	III	IV
r_t	-0.0937 0.1565	-0.1127 0.0905	-0.0944 0.1534	-0.1238 0.0629	-0.0966 0.1440
x_t^0	0.0020 0.0000	0.0019 0.0000	0.0020 0.0000	0.0017 0.0000	0.0020 0.0000
$r_t \ln\left(T_t\right)$	0.0032 0.8493	0.0054 0.7441	-0.0002 0.8455	0.0068 0.6847	0.0035 0.8311
$x_t^0 \ln\left(T_t\right)$	-0.0002 0.0000	-0.0002 0.0000	0.0032 0.0000	-0.0002 0.0000	-0.0002 0.0000
$d_t^S x_t^0$		0.0009 0.0000	0.0002 0.1069	0.0007 0.0000	0.0005 0.0010
	Dependent variable x_t^0				
r_t	85.0403 0.0000	85.3423 0.0000	84.8944 0.0000	87.8353 0.0000	85.1552 0.0000
x_t^0	0.4388 0.0000	0.4404 0.0000	0.4345 0.0000	0.4607 0.0000	0.4404 0.0000
$r_t \ln\left(T_t\right)$	-10.6027 0.0000	-10.6354 0.0000	-10.5960 0.0000	-10.9681 0.0000	-10.6174 0.0000
$x_t^0 \ln\left(T_t\right)$	0.0039 0.4218	0.0038 0.4303	0.0043 0.3729	0.0032 0.5062	0.0038 0.4298
$d_t^S x_t^0$		-0.0139 0.3597	0.0738 0.0011	-0.0480 0.0000	-0.0250 0.2402

Table 5(b)					
Coefficient Estimates – 5 Year Note The numbers in this table report coefficient estimates for the VAR model $r_t = \sum_{i=1}^{5} a_i^r r_{t-i} + \sum_{i=1}^{5} b_i^r r_{t-i} \ln(T_{t-i}) + \sum_{i=0}^{5} c_i^r x_{t-i}^0 + \sum_{i=0}^{5} d_i^r x_{t-i}^0 \ln(T_{t-i}) + \sum_{i=0}^{5} e_i^r x_{t-i}^0 D_{t-i}^S + v_{1t}$ $x_t^0 = \sum_{i=1}^{5} a_i^x r_{t-i} + \sum_{i=1}^{5} b_i^x r_{t-i} \ln(T_{t-i}) + \sum_{i=1}^{5} c_i^x x_{t-i}^0 + \sum_{i=1}^{5} d_i^x x_{t-i}^0 \ln(T_{t-i}) + \sum_{i=1}^{5} e_i^x x_{t-i}^0 D_{t-i}^S + v_{2t}$ Estimated from data for the 5-year US Treasury note, May - December 1998. The coefficient reported is the sum of the estimated coefficients and the number in parenthesis is the p-value of a Wald test for significance of this sum.					
Lagged variables	Dependent variable r_t				
	Bench-mark	Johnson-Lowen-stein	exposed banks stock returns	Wide credit spreads	swap yield increase
		I	II	III	IV
r_t	-0.3498 0.0000	-0.3670 0.0000	-0.3508 0.0000	-0.3865 0.0000	-0.3528 0.0000
x_t^0	0.0032 0.0000	0.0031 0.0000	0.0032 0.0000	0.0028 0.0000	0.0032 0.0000
$r_t \ln(T_t)$	0.0681 0.0002	0.0706 0.0001	0.0683 0.0002	0.0736 0.0000	0.0686 0.0001
$x_t^0 \ln(T_t)$	-0.0002 0.0000	-0.0002 0.0000	-0.0002 0.0000	-0.0002 0.0000	-0.0002 0.0000
$d_t^S x_t^0$		0.0015 0.0000	0.0005 0.0293	0.0013 0.0000	0.0007 0.0042
	Dependent variable x_t^0				
r_t	61.536'8 0.0000	61.8435 0.0000	61.4704 0.0000	64.4793 0.0000	61.7067 0.0000
x_t^0	0.4021 0.0000	0.4055 0.0000	0.4007 0.0000	0.4260 0.0000	0.4045 0.0000
$r_t \ln(T_t)$	-9.1419 0.0000	-9.1860 0.0000	-9.1313 0.0000	-9.5651 0.0000	-9.1663 0.0000
$x_t^0 \ln(T_t)$	0.0077 0.0900	0.0075 0.0982	0.0078 0.0852	0.0078 0.0865	0.0076 0.0932
$d_t^S x_t^0$		-0.0288 0.0364	0.0336 0.1100	-0.0737 0.0000	-0.0489 0.0121

Table 5(c)					
Coefficient Estimates – 10 Year Note The numbers in this table report coefficient estimates for the VAR model $r_t = \sum_{i=1}^{5} a_i^r r_{t-i} + \sum_{i=1}^{5} b_i^r r_{t-i} \ln(T_{t-i}) + \sum_{i=0}^{5} c_i^r x_{t-i}^0 + \sum_{i=0}^{5} d_i^r x_{t-i}^0 \ln(T_{t-i}) + \sum_{i=0}^{5} e_i^r x_{t-i}^0 D_{t-i}^S + v_{1t}$ $x_t^0 = \sum_{i=1}^{5} a_i^x r_{t-i} + \sum_{i=1}^{5} b_i^x r_{t-i} \ln(T_{t-i}) + \sum_{i=1}^{5} c_i^x x_{t-i}^0 + \sum_{i=1}^{5} d_i^x x_{t-i}^0 \ln(T_{t-i}) + \sum_{i=1}^{5} e_i^x x_{t-i}^0 D_{t-i}^S + v_{2t}$ Estimated from data for the 10-year US Treasury note, May - December 1998. The coefficient reported is the sum of the estimated coefficients and the number in parenthesis is the p-value of a Wald test for significance of this sum.					
Lagged variables	Dependent variable r_t				
	Bench-mark	Johnson-Lowen-stein	exposed banks stock returns	Wide credit spreads	swap yield increase
		I	II	III	IV
r_t	-0.4852 0.0000	-0.4904 0.0000	-0.4845 0.0000	-0.5110 0.0000	-0.4881 0.0000
x_t^0	0.0054 0.0000	0.0053 0.0000	0.0054 0.0000	0.0047 0.0000	0.0053 0.0000
$r_t \ln(T_t)$	0.0861 0.0000	0.0870 0.0000	-0.0003 0.0000	0.0905 0.0000	0.0866 0.0000
$x_t^0 \ln(T_t)$	-0.0003 0.0074	-0.0003 0.0063	0.0859 0.0079	-0.0003 0.0066	-0.0003 0.0074
$d_t^S x_t^0$		0.0015 0.0003	0.0007 0.1360	0.0019 0.0000	0.0025 0.0002
	Dependent variable x_t^0				
r_t	45.7519 0.0000	45.9931 0.0000	45.7469 0.0000	46.6623 0.0000	45.8536 0.0000
x_t^0	0.2765 0.0000	0.2817 0.0000	0.2750 0.0000	0.2998 0.0000	0.2787 0.0000
$r_t \ln(T_t)$	-8.0131 0.0000	-8.0465 0.0000	-8.0155 0.0000	-8.1470 0.0000	-8.0253 0.0000
$x_t^0 \ln(T_t)$	0.0178 0.0006	0.0181 0.0005	0.0179 0.0006	0.0177 0.0007	0.0178 0.0006
$d_t^S x_t^0$		-0.0705 0.0001	0.0401 0.1494	-0.0657 0.0000	-0.0570 0.0323

Figure 1

Price and trading volume of the on-the-run 5-year note on December 4, 1998

The upper panel graphs the bid-ask spread at the end of each five minute interval between 7:30 AM and 5:00 PM. The lower panel reports total dollar volume of trading ($ millions) occurring within each five minute interval.

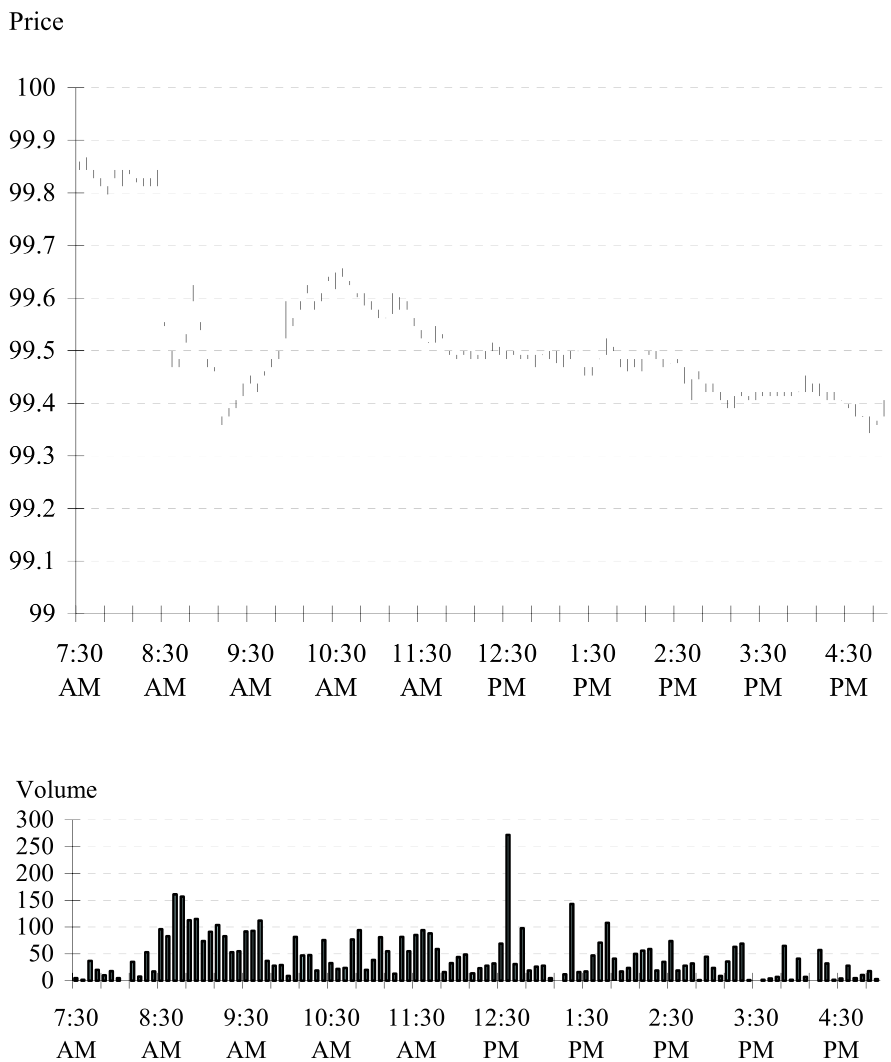


Figure 2

Accumulated impulse responses of returns to a positive trade shock – Baseline Model.

The solid black line graphs the impulse response of a trade shock on returns on normal days. The dotted line graphs the impulse response on the indicated set of stress days. The solid gray line graphs the impulse response to a shock on the given stress day, when the time between trades is adjusted to its stress-day level.

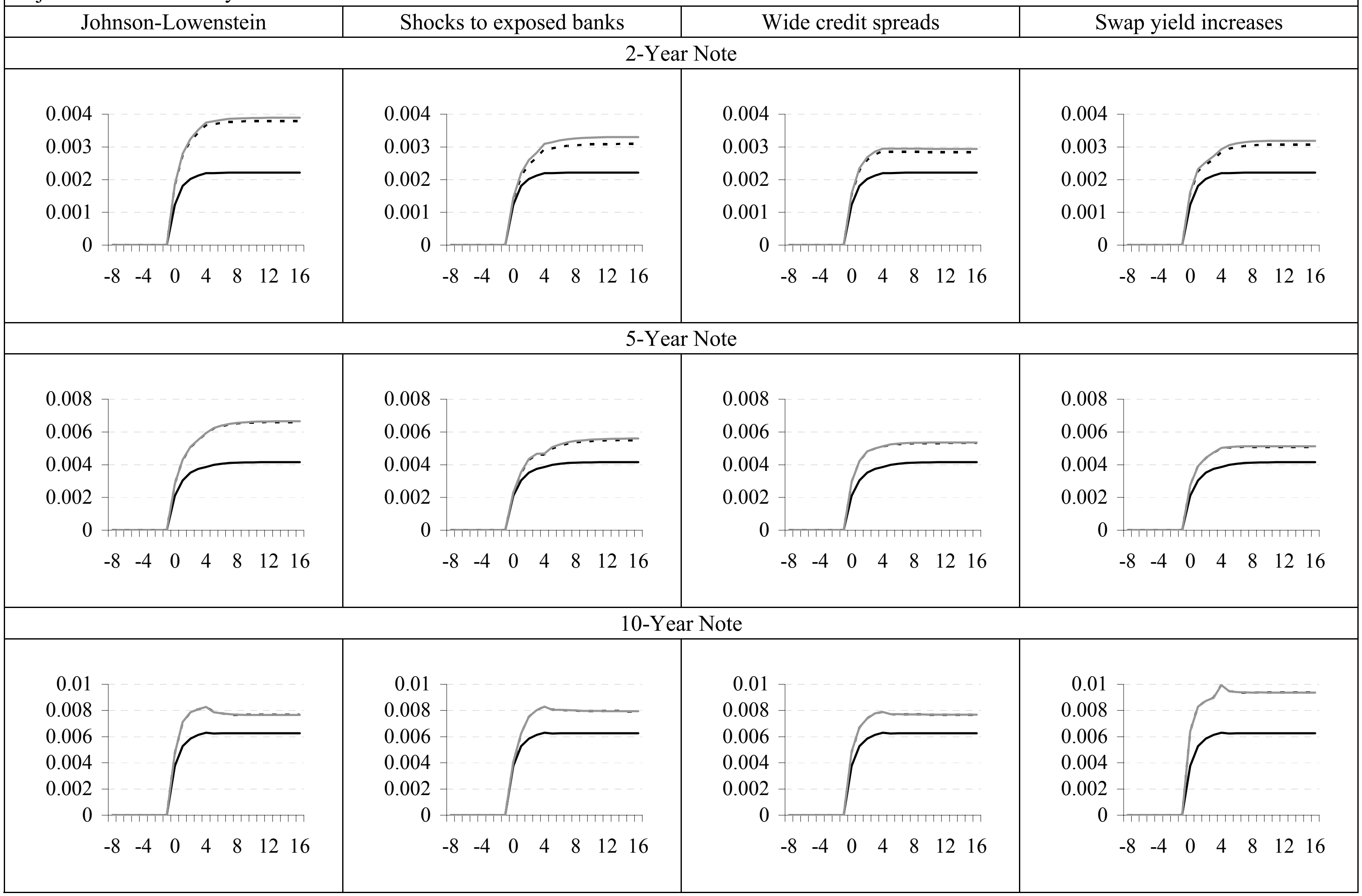


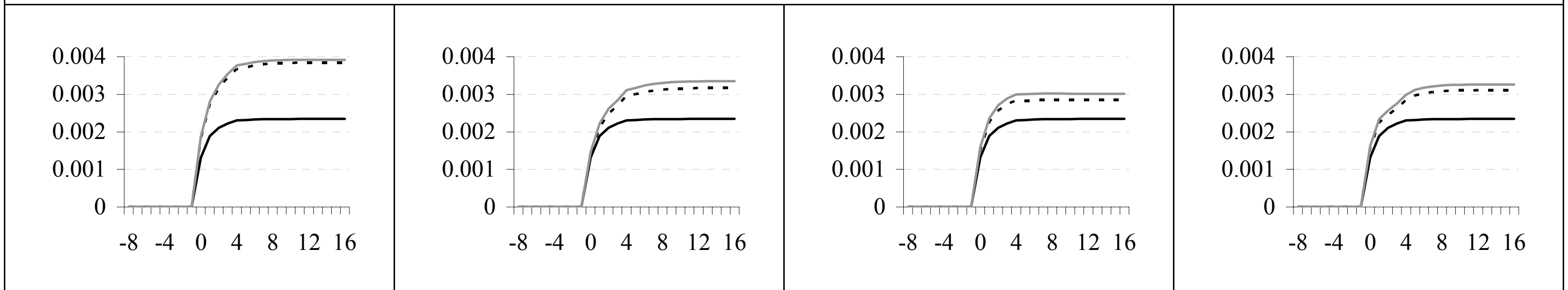
Figure 3

Accumulated impulse responses of returns to a positive trade shock – Extended Model.

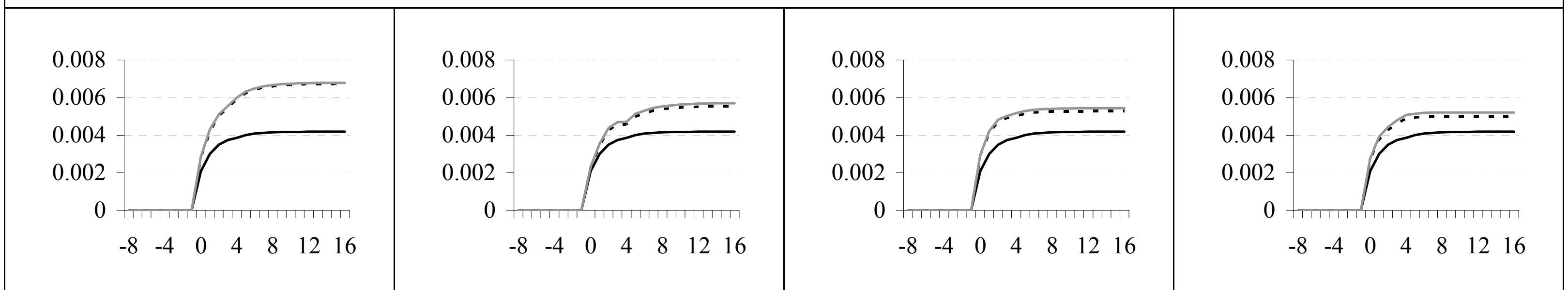
The solid black line graphs the impulse response of a trade shock on returns on normal days. The dotted line graphs the impulse response on the indicated set of stress days. The solid gray line graphs the impulse response to a shock on the given stress day, when the time between trades, bid-ask spread, and level of depth is adjusted to its stress-day level.

Johnson-Lowenstein	Shocks to exposed banks	Wide credit spreads	Swap yield increases

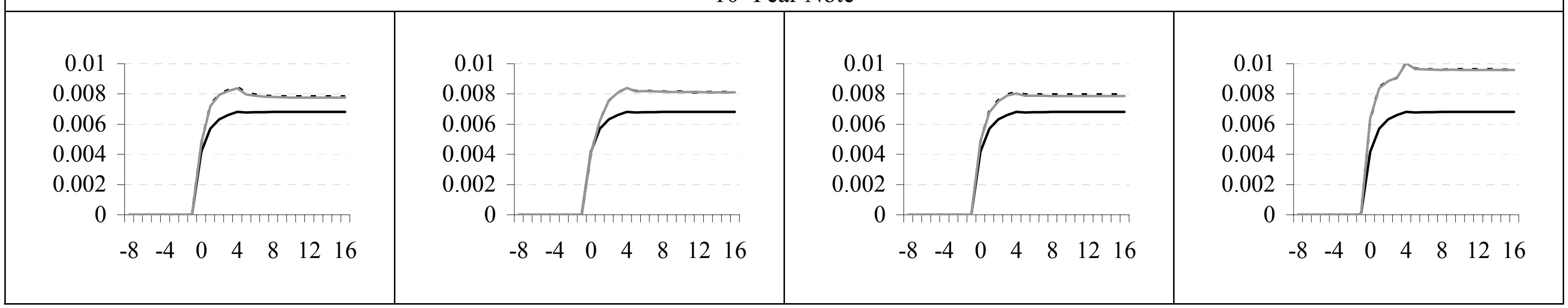
2-Year Note



5-Year Note



10-Year Note



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