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From Trade-to-Trade in US Treasuries*

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Abstract

The aim of this paper is to model the trading intensity of the US Treasury bond market which has a unique expandable limit order book which distinguishes its structure from other asset markets. An analysis of tick data from the eSpeed database suggests that the US bond market displays a greater degree of clustering in trade durations than is evident in other asset markets. Duration is affected by the presence of news particularly in the hour following the release of scheduled news to the markets. Finally, the length of time taken to complete a given transaction, or 'workup', has a measurable impact on the trade duration.

Keywords: US Treasuries, trade duration, workups, news.

JEL Classification: C22, G14.

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1 Introduction

The intensity of the trading process in stock and foreign exchange markets has received considerable attention in the literature. In general, trade durations are characterised by clustering; short (long) durations between transactions follow short (long) durations. Market microstructure explanations for autocorrelation in durations may be found in Easley and O'Hara (1992), Admati and Pfleiderer (1988) and Foster and Viswanathan (1990).

The intensity of trading in US bond markets is, to the best of the authors' knowledge, undocumented. This is surprising on two fronts: first, the US bond market is a major provider of global liquidity and an important benchmark referenced by many market participants making it arguably the most important financial market (see Goodhart and O'Hara, 1997). Second, the US bond market possesses unique trading arrangements which mean that characterizing its behaviour in transaction time provides an interesting extension to the trade duration literature. Specifically, the secondary market for US Treasuries operates under a unique expandable limit order book whereby the volume for each trade is individually negotiated (called the 'workup' phase - see Section 1.1 for details). Studying the superseded voice-over protocol, Boni and Leach (2004) examine depth discovery and price improvement, arguing that when the order book is expandable, informed traders will use small limit orders to search for trading counter parties. Once they have identified a dealer who has indicated a willingness to trade, they will enter into quantity negotiations, i.e. a workup will take place. This process affords greater anonymity to informed traders in comparison to a conventional order book. The placement of a large limit order may signal information to the market.[1] Thus, Boni and Leach (2004) assign an informational role to workup in that the average workup time will increase and stay high for as long as the private signal has value. They use this in examining price and depth discovery, but do not model trade duration or its interaction with workup.

To examine trade duration in the market for US Treasury bonds, this paper develops a threshold Autoregressive Conditional Duration model (ACD). The ACD was introduced by Engle and Russell (1998). [2] High frequency US Treasury data sampled

[1] An alternative strategy would be to engage in stealth trading, whereby trades are broken up into smaller and less conspicuous lots (see Barclay and Warner, 1993).

[2] Other applications of ACD models may be found in Engle and Russell (1997, 1998), Engle (2000),

over the period January 3, 2006 to October 10, 2006 is used to estimate an ACD(p, q) model which is then extended to include the workup period as an additional source of information.

The threshold ACD model is also extended to incorporate information on the arrival of news and the size of the news surprise, particularly around the 8.30am period, when the majority of the important news releases occur. Regularly scheduled macroeconomic news has been shown to have significant impact on the behaviour of agents in the bond markets (see Fleming and Remolona, 1999, Balduzzi, Elton and Green, 2001, Green, 2004, Simpson and Ramchander, 2004, Pasquariello and Vega, 2007 for spot markets and Kuttner, 2001 and Andersen, Bollerslev, Diebold and Vega, 2007 *inter alia* for Treasury futures).

The results of this paper may be summarised as follows; We find that trade duration for US Treasuries display different properties to those documented for other asset markets. Specifically, the US bond market displays a far greater degree of persistence in trade durations. Further, duration is affected by the presence of news on any given day and particularly in the hour following the scheduled release of news to the markets, although the size of the news surprise is not found to be significant. Finally, the length of time taken to complete a given transaction has a measurable impact on the time between transactions. Specifically, we find that a long workup tends to be associated with a shorter time to the next transaction. Further, the time taken to workup a trade has a greater impact on reducing the expected adjusted duration than does the arrival of news in the form of scheduled macroeconomic news announcements.

The remainder of this paper proceeds as follows. Section 1.1 provides a detailed description of the trading process in the US bond market. Section 2 introduces the dataset and characterises the data in terms of transaction size, intensity and workups. A comprehensive examination of the data is undertaken and the analysis suggests that the information content of news arrival, volume and workup time each have a role to play in understanding the duration of transactions in the US Treasury market, while news surprises do not. Building on this preliminary analysis, Section 3 proceeds to develop and estimate a formal model of US bond market trade durations. We modify

Bauwens and Giot (2000), Zhang, Russell, and Tsay, 2001, Bauwens and Veredas (2004), Xu, Chen and Wu (2005) and Bauwens (2006). A survey of the ACD literature may be found in Engle and Russell (2004) and Bauwens and Hautsch (2007).

this model to incorporate the workups that are unique to the US Treasury market. In the fourth section we examine a number of testable hypotheses from the literature. Section 5 uses the estimates to build a profile of the expected duration of trades in the market in scenarios involving news releases and workups. Finally, Section 6 concludes the paper.

1.1 The Trading Process

Trading in US Treasury bonds begins by participants committing to trade a given volume at a stated price by placing orders on the electronic system. Typically, orders are for a minimum of US$1 million and the posting trader does not incur transaction costs. When a trader hits (takes) a passive bid (ask) displayed on the system, the two participants are committed to trade *at least* the posted volume at that price. They also have a short exclusive period to negotiate additional volume, after which other market participants may enter into the active trade to expand volume. Hence, the volume traded is 'expandable' and only one trade is ever in progress at one time. A trade ends when there is a sufficient time of inactivity, that is nobody expands volume at the current active price. This means it is still possible to observe distinct trades at the same price.

This electronic trade system evolved to replace the voice over protocol arrangement of the GovPX system described for data from the 1990s in Boni and Leach (2004). In the voice over protocol system, a single trader responded to the posted opportunity and the two participants individually negotiated any increase in total volume at the agreed price by phone. A number of these pairs of trading opportunities could occur contemporaneously and thus overlapping trades and workups occurred, which Boni and Leach (2004) use as a measure of impatience. While the voice over protocol platform still exists, it carries negligible volume.

A representation of the current trading process on the electronic platform for three hypothetical transactions is shown in Figure 1. Transaction 1 begins at t_0, when a market participant agrees to transact at a price and quantity posted to the electronic communication network, hereafter ECN . Additional quantity is then incrementally negotiated and the transaction is completed when a sufficiently small period of time has elapsed without further deals being struck (f_0).[3] The workup, $W_i = f_i - t_i$ is the time between the start and finish of the transaction and may differ for every transaction depending on the length of the negotiations over additional volume. For the hypothetical transactions shown in the figure, the first and third transactions contain workup, while the second transaction is for the posted volume only, with no subsequent workup. Further, the first transaction has a shorter workup than the third transaction. Note that the length of the workup does not necessarily reflect the size of the traded volume and this relationship is considered more fully in Section 2.2.

Trade duration is defined in the existing foreign exchange and equity market applications as the time between initiations of sequential transactions. For consistency this is the definition adopted here for the bond market. There are other potentially interesting time measures in this market: the time between the ends of transactions or the end of the previous trade and the beginning of the next. Modelling the interaction between the different time processes is an interesting avenue for future research.

2 Descriptive Statistics

One of the most significant difficulties facing high frequency studies of US bond markets, has been obtaining a suitable sample of data. Until recently, the GovPX database was the main source of data. The use of GovPX data however, brought with it a number of problems related to identifying trades, matching the actual bid-ask spread to trades and, most importantly, correctly calculating the volume of trade. Since 2000 however, US bond market trading has changed significantly and is now dominated by the ECNs of Cantor Fitzgerald and ICAP. The eSpeed (now BGCantor) and BrokerTec databases provide trading information for each of these markets and Mizrach and Neely (2006) find that there are qualitatively few differences between the two.[4]

In this paper, we draw on the eSpeed dataset, which provides 10 millisecond shots of the transaction process (the maximum updating frequency that the traders using this platform see in real time). We consider trading in the 2, 5 10 and 30 year benchmark

[3]Note that consecutive trades may be negotiated at the same price as in some circumstances it is advantageous for a market participant to wait to initiate a new trade at the same price.

[4]Mizrach and Neely (2006) provide details of these two US ECN bond markets. They report that the market is split 60/40 in favour of the ICAP ECN. The more recent evidence of Jiang et al (2007) and Dungey et al (2009) however, suggests the market is more evenly split.

on-the-run Treasuries over the sample period January 3, 2006 to October 10, 2006. This yields a minimum of 116,479 observations for the 2 year maturity and a maximum of 273,898 observations for the 10 year maturity.[5] The trading day is defined as beginning at 7:30am New York time and ending at 5:30pm.

Insights into the nature of our dataset may be obtained by considering the average total trading volume and average trade size for trades in half hour periods across the trading day (see Figures 2 and 3). The total volume traded and average trade size both increase substantially from the open to peak at 8:30am for all maturities, with a smaller and less pronounced peak at 10:00am. These peaks coincide with the two scheduled major US macroeconomic news announcement times, which the previous literature has linked to higher transaction volume and even disruptions to the pricing process; see for example Fleming and Remolona (1997), Balduzzi et al (2001), Simpson and Ramchander (2004), Pasquariello and Vega (2007), Andersen et al (2007) and Dungey, McKenzie and Smith (2009).

2.1 Durations

While the eSpeed database records a great deal of information, our focus is specifically on the time between transactions. A basic description of the trading intensity in this dataset is given in Table 1. In the sample period, the number of trades per day averages between 623 for the 2 year maturity to 1465 for the 10 year.[6] The largest trades are reported in the shorter 2 year maturity, where both the average and the maximum are substantially greater than for other maturities. The smallest average and maximum volumes are reported for the 30 year. Average and maximum trade size tend to decrease as the term to maturity increases.

Table 1 also summarises the raw durations associated with each maturity. The 5 and 10 year bond contracts have the shortest average duration (around 24 seconds), while the 2 year maturity exhibits the longest average duration (55.86 seconds). The average duration for trades in half hour periods across the trading day is presented in Figure 4. From the beginning of the trading day, durations fall until 8.30am and subsequently

[5] Previous ACD models have been estimated with 3 months of data, see Engle and Russell (1998), Zhang, Russell and Tsay (2001) and Bauwens and Veredas (2004).

[6] Although Cantor-Fitzgerald's reputation is as a long end specialist, Jiang et al (2007) compares the total turnover by maturity across the two electronic platforms and find that any difference is marginal.

lengthen as the trading day progresses, with a slight deviation at 10.00am. As has been previously discussed, the 8.30am and 10.00am periods are the two scheduled major macroeconomic news announcement times in the US.

The IBM equity data in Engle and Russell (1998) reveals the commonly observed hump shape in duration across the 9:30am to 4pm period. The bond data reveals the same diurnality in this interval. What distinguishes the bond data from the standard trading pattern of stocks is the low trading intensity (longer durations) in the periods prior to the stock market opening and after the stock market closing. These differences are apparent in Figure 4.

Intradaily data is typically characterised by strong diurnality (see Engle and Russell, 2004), which may bias any estimation results. Such patterns are a clear feature of the bond durations data. To account for these intradaily effects, we follow the approach of, *inter alia*, Engle and Russell (1998, 2004) and Zhang, Russell and Tsay (2001) by constructing diurnalised estimates of duration (and workup times). Defining the raw duration between the i^{th} and $i-1^{th}$ transactions as $x_i = t_i - t_{i-1}$, then the adjusted duration is:

$$x_i^* = \frac{x_i}{\Phi\left(t_{i-1}\right)}, \tag{1}$$

The deterministic effect on trade durations due to the time of day is defined as the expected duration conditioned on time-of-day $\Phi\left(t_{i-1}\right) = E\left(x_i|t_{i-1}\right)$. This expectation is obtained by averaging the durations over thirty minutes intervals for the trading day. A cubic spline is employed to smooth the time of day function across the thirty minutes intervals. By construction, the mean of x_i^* is approximately 1.

A brief summary of the diurnalised duration for each maturity is presented in Table 1, and the average daily pattern of half hour adjusted duration for each maturity is plotted in Figure 5. Figure 5 shows that the diurnal pattern in the raw durations is removed by smoothing process described above. Table 2 presents a more detailed summary of the adjusted durations for the 2, 5, 10 and 30 year maturities including the number of trades (n), sample average (μ), p-value for a test of the null of a sample average of zero (in parenthesis) and standard deviation (σ^2). The results of a battery of Ljung-Box tests for p^{th} order serial correlation in x_i^* and the corresponding squares are also presented in Table 2 and the results uniformly reject the null hypothesis of no serial correlation. Thus, there is clear evidence of significant persistence in the filtered data and the results show considerable structure in the adjusted durations.

2.2 Workups

For each transaction, there is potentially a period of workup. Table 1 presents a summary of the average workup. Unlike the average of the raw durations which are distinctly higher for the 2 and 30 year maturities, the average of the raw workup times is similar across all maturities (approximately 2 seconds). Differences do exist however, when comparing the range of raw workup times. The 5 and 30 year contracts have maximum workup values that are approximately five times larger than those of the 2 and 10 year bonds. Similar to total traded volume and average trade size, the average workup (Figure 6) increases from the open to peak at 8:30am for all maturities and then proceeds to decline throughout the rest of the day, with the exception of a smaller and less pronounced peak at 10:00am. To account for this time dependency, we construct diurnalised workup times, denoted W_i^*. Plots of the daily average of the half hour values of adjusted workups for each maturity are presented in Figure 7. The variation in the adjusted workup is greatly reduced from the raw workup data, but there remains minor visible diurnality around the end of the trading day.

Table 3 presents a detailed summary of the workup process, distinguishing between transactions with and without a workup. The majority of trades occur without any workup - over 60% of the transactions for the 2 and 30 year bonds and around 54% for the 5 and 10 year bonds. Trades without workup however, are typically for small volumes - the average size of a trade with no workup is less than half the average trade size for the 2, 5 and 10 year notes, and under 60% of that for the 30 year bonds. Table 3 shows that up to 76.5% of dollar volume is discovered in trades which involve some workup. Boni and Leach (2004) report that 56.5% of the dollar volume in the superseded voice protocol trading system, GovPX, is discovered via the workup process. The data also suggest that larger volume does not necessarily result in more steps in the workup process. Recall that the average length of raw workup is two and a half seconds or less across all maturities (Table 1). When the large number of no workup transactions are accounted for, this figure rises by only around 1 second for any given maturity. By way of comparison, the fastest average workup time reported in Boni and Leach (2004) using GovPX data for 1997, is over four times greater.

The speed at which orders are filled in the ECN is substantially faster when compared to the voice protocol GovPX system. The eSpeed system does not allow overlapping transactions, hence the measure of impatience proposed by Boni and Leach is not applicable in this new architecture. Boni and Leach (2004) considered overlapping transactions (Boni and Leach, 2004, Table 2) and found substantial evidence of impatience with the queuing process that may result from the workup period. In their results, they find that one third of all transactions in their 5 year bond sample have overlap with the previous transaction, comprising some 18 percent of the total volume traded. Further, in the event that a new transaction begins before the completion of the previous transaction, a price improvement is likely to result.

The diurnality in workup times in Figure 6 shows a peak at 8:30am, which is the period of greatest market activity - both in terms of total volume and average trade size - and the lowest time between trades. An important question is the extent to which workup is proxying for volume. It is possible that a transaction that is twice as big may take twice a long to negotiate, in which case workup is not providing any additional information beyond that already contained in volume. Figure 8 records the number of transactions (log linearised vertical scale) for each trade size (measured in $US million on the horizontal axis) for all maturities. It is immediately obvious that the greatest number of transactions are for relatively small trade sizes and the number of transactions generally declines as the size of transaction increases in value. There are distinct spikes in number of transactions observed at trade sizes of $5m, $10m, $25m, $50m, each $50m increment from $100m to $300m and then at $400m and $500m. For larger volumes there are no further standard package sizes (Figure 8 is truncated at $500m). These relatively standard package sizes exhibit a workup time that is generally faster than similar sized, yet nonstandard trade volumes. For example, some of the longer workup periods recorded in the sample are for transactions of size $219m and $322m in the 5 year and $417m in the 30 year. In both cases there are higher volume transactions with lower workup times.

To highlight the diversity of the volume and workup relationship, we present some illustrative examples for the 5 year maturity. Figure 9 presents the distribution of observed workup times for transactions of different sizes - $5m, $10m, $25m and $100m (excluding those transactions with no workup), which Figure 8 identified as being common transaction sizes and represent a substantial number of trades in the database. These histograms highlight a surprising diversity of workup times given that each figure represents a homogenous trade size. For example, consider the histogram for \$25m transactions presented in the lower left hand panel of Figure 9. There is a clear clustering of transactions at the 2 second mark, but there are many transactions that take less time to negotiate and also a substantial number of \$25m dollar transactions that take longer, including a large clustering at the 4 second mark, with some taking over 10 seconds to negotiate. The same broad characterization of the data applies to all maturities and all transaction sizes. Based on the evidence there is enough variation from the workup time variable after controlling for trade size to suggest that workups may be informative about market conditions beyond measures of volume.

2.3 News Effects

A substantial body of literature exists that has focussed on the effect of prescheduled news releases on the US Treasury market using intradaily data. Fleming and Remolona (1997, 1999), Balduzzi et al (2001), Simpson and Ramchander (2004) and Green (2004) all look directly at the impact of news releases on price in this market. Johannes (2004), Andersen et al (2007) and Dungey et al (2009), *inter alia*, specifically consider the relationship of pricing discontinuities (jumps) with news releases. The general consensus across these papers is that these prescheduled announcements contain important information which moves the market. Further, the sensitivity of the bond market to an announcement is related to the size of the surprise component of the news, which is usually measured as the difference between the anticipated value of the economic indicator and the actual estimate. These papers also conclude that the most important releases impacting the US Treasury markets are the 8:30am releases of the US CPI, PPI, retail sales, housing starts, GDP, durable goods and non-farm payrolls.

The previous analysis of durations and workups has presented clear evidence of diurnality at 8:30am (and to a lesser extent 10.00am), which coincide with the time at which the majority of news releases occur. This raises questions around (i) the extent to which these differences are driven by the existence of news, and (ii) whether this seasonality is deterministic and so may be exploited for modeling purposes (we consider this latter issue in the following section).

To begin the analysis, Figures 10 and 11 give the diurnal picture of the average duration and workup time (in seconds) for the 5 year maturity Treasury for all days, no news days and news days, where the news announcements are those listed previously. The results for the other maturities are qualitatively consistent with those presented and are not presented to conserve space. Figures 10 and 11 highlight the difference between a news release day and a non-news release day in terms of trading intensity, in particular around the 8.30am period. For news release days, the average workup (duration) is greater (lower) at 8.30am than for any other time of the day. Where the day does not contain a regularly scheduled release of news however, the average workup increases at the open and is fairly constant until lunch time, at which point it declines toward the close where the lowest average values are observed. The average time between trades on the other hand, decreases at the open, is fairly constant until lunch time and then progressively increases to record its highest levels at the close.

Insights into the impact of macroeconomic news announcements on bond market trading behaviour can be garnered by considering Figure 12, which presents the distribution of workups for 5 year maturity US Treasury bond transactions on non-news (column 1) and news (column 2) days, grouped by transaction size (rows 1 corresponds to a transaction volume of between \$5m and \$10m, row 2 from \$10m up to \$20m, and row 3, greater than \$20m). The data for the other maturities are qualitatively similar and are not presented to conserve space. This figure illustrates some general characteristics of the data. First, the clustering of workup length at around 2 and 4 seconds is a feature of both news and non-news days. Second, although the number of trades differs across news and non-news days, there is no obvious change in the distribution of the workup. Thus, while the earlier results suggest that news days are characterised by a higher volume and intensity of trading, these results show that this does not translate into any discernible difference in the characterization of the workup process across all trades.

3 A Model of Trade Durations

A standard univariate ACD(p, q) model to capture the clustering and serial correlation observed in time duration in high frequency market data model is given by

$$\begin{aligned} x_i^* &= \psi_i \varepsilon_i, \\ \psi_i &= \mu + \sum_{j=1}^{p} \gamma_j x_{i-j}^* + \sum_{j=1}^{q} \omega_j \psi_{i-j} \end{aligned} \tag{2}$$

where ψ_i is the expected value of duration given the information set, and the error term, ε_i, follows some process to be defined below. This follows the specification proposed by Engle and Russell (1998).

An ACD(1,1) model is specified as a starting point for the analysis, as it has been found in the previous literature to provide a satisfactory representation of financial data (see Hautsch, 2006, for example). Following Engle and Russell (1998), the distribution function of ε_i on $(0, \infty)$ is specified as a Weibull distribution.[7] Table 4 presents the results of estimating (2), where $p = 1$, $q = 1$ is specified, i.e. a WACD(1,1), for the 2, 5, 10 and 30 year US Treasuries.[8] The results in Table 4 indicate that the parameters in the duration model are all significant at the 1% level or better. The expected value of the adjusted duration is given as $E(x_i^*) = \mu / (1 - (\gamma_1 + \omega_1))$ and tends to rise with the maturity up to 10 years, but then declines quite dramatically for the 30 year maturity. The persistence of the adjusted duration is given by the sum of the coefficients in the duration process, $\rho(x_i) = \gamma_1 + \omega_1$. Across all maturities, the sum of the coefficients is high, but less than unity, which is consistent with the findings of the previous literature for other markets (see *inter alia* Engle and Russell, 1998, Engle, 2000, and Bauwens and Veredas, 2004). The persistence of trade durations is highest in the 10 year contract and lowest in the 2 year contract.

Engle and Russell (1998) suggest the Ljung-Box statistic as an appropriate diagnostic for the ACD model. To this end, the Ljung-Box statistics are reported in the middle of the table and they suggest the presence of significant serial correlation in the

[7] A number of alternative distributional functions of ε_i have been considered in the literature including an exponential distribution, Burr distribution (see Grammig and Maurer, 2000) and generalized gamma distribution (see Lunde, 2000).

[8] The Weibull nests the exponential distribution, so that when the shape parameter $\alpha = 1$, the conditional log likelihood of the WACD model collapses to that of an exponential ACD. The null hypothesis $H_0 : \alpha = 1$ was rejected for all maturities, which indicates that the hazard function is not a constant.

standardised innovations and their corresponding squares. This is a common feature of ACD modelling as several authors (Engle and Russell, 1998; Engle, 2000; Zhang, Russell, and Tsay, 2001; Fernandes and Grammig, 2006 among others) report substantial difficulties in completely removing dependence in the residual series.

To control for the excess serial correlation in the WACD model, we consider a higher order specification. The use of higher order autocorrelation structures is not unusual as Engle and Russell (1998), for example, specified an ACD(2,2) process when modeling their IBM transactions data. In the case of the bond market data, even longer lag lengths are required to obtain a satisfactory fit. Table 5 presents the estimation results for a WACD(5,5) model. In terms of the coefficient estimates, the WACD(5,5) model shows an increase in the sum of the autoregressive parameters, $\sum_{j=1}^{5} \gamma_j$ when compared to the single AR(1) parameter γ_1 reported in Table 4. By way of contrast however, the clustering effects given by $\sum_{j=1}^{5} \omega_j$ in the WACD(5,5) model are generally slightly smaller than the single clustering effects in the WACD(1,1). The expected value of the adjusted duration, given by $E(x_i) = \mu / \left(1 - \left(\sum_{j=1}^{5} \gamma_j + \sum_{j=1}^{5} \omega_j\right)\right)$ for the WACD(5,5) is about 25% lower than the WACD(1,1). The exception is the 30 year maturity, where the expected adjusted duration has risen by almost 4 times when compared to the previously discussed estimate. In this case, the expected adjusted duration for the 30 year maturity is somewhat greater than that of the other maturities. The persistence of the adjusted duration, given by the sum of all the γ_j and ω_j parameters is not substantially different to the earlier estimates, remaining high and tending to increase with maturity.

An examination of the diagnostics for this WACD(5,5) model reveals that, while the Ljung-Box statistics are improved, at conventional statistical levels they continue to reject the null of no serial correlation. Despite this rejection of the null, the test scores are nevertheless consistent with those reported in other studies for models that are deemed to have relatively 'good' performance (see Engle and Russell, 1998, *inter alia*).

The analysis of the previous sections suggests that workup and the information content of news arrival may each have a role to play in understanding the duration of transactions in the US Treasury market. The WACD(5,5) model may be extended to consider the impact of news arrival and the workup process on transaction duration using the threshold ACD model:

$$\begin{aligned} x_i^* &= \psi_i \varepsilon_i, \qquad (3)\\ \psi_i &= \mu + \beta_1 A_i + \beta_2 N_i + \beta_3 I_{W^*,i-1} + \beta_4 I_{W^*,i-1} W_{i-1}^* + \beta_5 I_{W^*,i-1} N_i \\ &\quad + \sum_{j=1}^{p} \gamma_j x_{i-j}^* + \sum_{j=1}^{q} \omega_j \psi_{i-j} + \sum_{j=1}^{r} \lambda_j \left(N_i x_{i-j}^* \right) \end{aligned}$$

where A_i takes the value 1 if x_i^* occurs on a day with a prescheduled news announcement, and zero otherwise. N_i is a dummy variable that takes the value of 1 if x_i^* occurs between 8:30am and 9:30am on a news day. $I_{W^*,i-1}$ is a dummy variable that identifies the presence of a workup in the previous transaction, while $I_{W^*,i-1}W_{i-1}^*$ will take the value of the last adjusted workup time, or zero. $I_{W^*,i-1}N_i$ is an interaction of the two dummy variables, identifying the impact of a workup in the previous transaction during the news announcement period. Finally the terms in $N_i x_{i-j}^*$ capture changes in the persistence of a shock to trade intensity around the news announcement time.[9]

The period 8:30 to 9:30am is specified as it encompasses the period over which the market responds to news - Andersen et al (2007) find that the majority of the price impact has dissipated within 5 minutes, although volatility impact is present for 30 minutes. Balduzzi et al (2001) however, record volume and volatility responding to news releases for up to 60 minutes. Thus, this model allows for durations to have a different dynamic process on days with a scheduled macroeconomic news announcement. The announcements used are the 8:30am releases of the US CPI, PPI, retail sales, housing starts, GDP, durable goods and non-farm payrolls.

Equation (3) is estimated and the results are presented in Table 6 and 7. The estimated intercept $\hat{\mu}$, increases with maturity. The coefficient sums $\sum_{j=1}^{5} \gamma_j$, $\sum_{j=1}^{5} \omega_j$ and $\sum_{j=1}^{5} \lambda_j$ are all significant indicating that the persistence of a shock to trade durations may vary depending on whether the shock arrives between 8:30am and 9:30am on a news announcement day. The Ljung-Box statistics presented in Table 7 are vastly improved over those estimated for the standard ACD models reported earlier and there is no evidence of misspecification. The implication of these results is that the ACD(1,1) and ACD(5,5) models are potentially misspecified conditional characterisations of the data. The only model that passes the diagnostic tests is the threshold ACD model

[9] Note that we control for end of day effects in that workups on previous transactions refer to workups on the same day. In preliminary work, terms in $A_i x_{i-j}^*$ and $I_{W^*,i-1} x_{i-j}^*$ were also included but were nowhere significant. In the interests of brevity and clarity we omit these results.

(3). It follows that the release of new information to the market may have significant impact on trading intensity, causing the expected trade duration to vary systematically around the time of a scheduled news announcement. In the next section we test a series of hypotheses about the relationship between trade durations, workups and news announcements. Moreover, we expand (3) to consider whether surprises, and not just announcement effects, are important determinants of the expected time interval between trades.

4 Hypothesis Tests

Equation (3) represents a richer dynamic characterisation of trading duration than the typical ACD(p, q) model. Drawing on the existing literature, we add a potential role for announcement days, workup effects and a time of day impact associated with the 8:30-9:30am period each day when most macroeconomic news announcements are scheduled. In this section we test for the significance of these effects.

4.1 *The joint importance of workup and news in determining trade duration*

The ACD(p, q) implies that the adjusted trade duration, x_i^* is solely determined by past realisations of x_i^* and lags of the expected value of the trade duration, ψ_i.The first test considers whether the strong implications of the ACD(p, q) are satisfied for our data. To do this we conduct a test on the null hypothesis of:

$$H_0^1 : \text{ The correct model is a simple ACD}(p, q).$$

Under H_0^1 there are no possible impacts on trade durations from either the announcement of news or the presence of a workup or both. Given the results reported in Section 3 we anticipate that the null is likely to be rejected. This hypothesis is tested using a Wald test of the restriction $H_0^1 : \beta_j = \lambda_j = 0, \forall_j$ and is distributed as $\chi^2(10)$.

The calculated test statistics for each maturity reported in Table 7 are strongly statistically significant at all usual levels of confidence (marginal significance level 0.0000). This implies that the WACD(5,5) model obtained under the restrictions would represent a misspecified conditional characterization of the data; durations are affected by the presence of a workup or the announcement of news or both. We now proceed to test each of these components separately.

4.2 *The importance of workup*

4.2.1 *The presence of workup*

The presence of workup indicates that greater volume than that initially posted at the bid or offer is being transacted. In the first instance, we wish to test whether the simple presence of workup is informative in modelling the trade duration. Specifically, whether the duration between trade i and the previous trade is affected by the presence of a workup in trade $i-1$. Green (2004) suggests that the delay imposed by the workup process may decrease the time to the next transaction. To this end, we examine the null hypothesis:

$$H_0^2 : \text{ The presence of a workup is irrelevant}$$

using a t-test on the significance of the coefficient β_3. Rejection of the null $H_0^2 : \beta_3 = 0$ implies that the presence of a workup impacts on the duration of a trade. Table 7 reports that, with the exception of the 2 year maturity, the null hypothesis H_0^2 is rejected; the presence of a workup in the previous transaction is a significant determinant of the i^{th} trade duration. For the 5, 10 and 30 year maturities a workup in the previous transaction tends to reduce the i^{th} trade duration as $\hat{\beta}_3$ is negative and significant, implying that the observation of increased volume over that initially posted significantly decreases the time to the next trade. This is consistent with the hypothesis in Green (2004).

4.2.2 *The time taken to workup*

The time taken to workup may also have an effect on the interval between trades. Extrapolating from Green (2004), a longer workup may cause impatience in the market, leading to a shorter duration to the next transaction. The influence of workup time is tested using the null hypothesis:

$$H_0^3 : \text{ The length of the workup time is irrelevant}$$

with a t-test for the significance of the coefficient $H_0^3 : \beta_4 = 0$. For each maturity the null hypothesis is rejected, see Table 7. There is a negative and significant relationship between the i^{th} trade duration and the workup time in the $i-1^{th}$ transaction. This evidence suggests that a longer time to finish the previous transaction via workup is associated with a shorter duration to the current transaction.

4.2.3 *The joint significance of workup*

Finally we test whether there is evidence for any workup effects in total, under the null hypothesis of:

$$H_0^4 : \text{ There are no workup effects}$$

using a $\chi^2(3)$ distributed Wald test of $H_0^4 : \beta_3 = \beta_4 = \beta_5 = 0$. This test, reported in Table 7, also allows for the possibility of an interaction between news arrival and workups impacting upon the duration between trades. This hypothesis of no workup effects on duration is rejected for each maturity for all usual levels of confidence.

4.3 *The importance of news announcements*

There is substantial evidence of the significant impact of news announcements on other aspects of bond market data, particularly returns and price behaviour; see Green (2004), Fleming and Remolona (1999), Dungey et al (2009), *inter alia.* To date, there has been no evidence on its effect on trading intensity. Here we conduct a number of tests for the impact of news on the time between trades.

4.3.1 *Announcement day effects*

The first test for whether duration is affected by the presence of a prescheduled macroeconomic news announcement on that day is stated as the null hypothesis:

$$H_0^5 : \text{ News announcement days are irrelevant}$$

Failure to reject H_0^5 implies that the scheduled news announcement days are not unusual. This hypothesis is tested using a t-ratio test of the restriction $H_0^5 : \beta_1 = 0$. The results reported in Table 7 fail to reject this null hypothesis for all maturities - there is no evidence that trade durations are different for days with and without a scheduled news announcement.

4.3.2 *Announcement time effects*

Prescheduled macroeconomic news announcements in the US market occur primarily at 8:30am. Estimates of the length of the impact of this news on price discovery in the bond market vary and may be as long as 60 minutes (Balduzzi et al, 2001). A diurnality effect is observed in Figure 4 in the period around 8:30am, and here we test whether the 60 minute period following the news announcement time in the market has a significant effect on trade duration using the null hypothesis of:

$$H_0^6 : \text{ News announcement time is irrelevant}$$

The restriction $H_0^6 : \beta_1 = \beta_2 = \lambda_j = 0, \forall_j$, is tested with a Wald test distributed as $\chi^2(7)$. The results reported in Table 7 suggest H_0^6 is rejected for all but the 5 year maturity at the 5% level of confidence.

4.4 *The effects of News Surprises*

The results presented in the previous section, suggest that the time of a news announcement is a significant determinant of trade duration. We now proceed to consider whether the degree to which new information has been anticipated by the market is an important determinant of the expected duration between transactions. Much of the existing literature on macroeconomic news and the bond market relates the market response to the extent of surprise in the news release, for example Dungey et al (2009) *inter alia*.

Define Z_i as the standardised surprise associated with any scheduled news announcement. Surprises are taken as the deviation of the actual announced value for the scheduled statistic from the expectation, which is collated from Bloomberg. As each news release has different units of measurement the usual approach is to standardise the surprises by the standard deviation of that particular release over the sample period. The relatively short (in macro news time) sample of high frequency data makes this less than satisfactory. Consequently, we have standardised the news releases with the standard deviation of each of the surprises collated for the period January 2002 to the end of our sample period. If the size of the surprise is a significant determinant of ψ_i then β_6 will be significant in

$$\begin{aligned} x_i^* &= \psi_i \varepsilon_i, \\ \psi_i &= \mu + \beta_1 A_i + \beta_2 N_i + \beta_3 I_{W^*,i-1} + \beta_4 I_{W^*,i-1} W_{i-1}^* + \beta_5 I_{W^*,i-1} N_i + \beta_6 Z_i \\ &\quad + \sum_{j=1}^{p} \gamma_j x_{i-j}^* + \sum_{j=1}^{q} \omega_j \psi_{i-j} + \sum_{j=1}^{p} \lambda_j \left(N_i x_{i-j}^* \right) \end{aligned} \tag{4}$$

Table 8 presents the results from the estimation of (4). The evidence strongly suggests that Z_i is not a significant determinant of ψ_i. The estimated standard errors obtained for $\hat{\beta}_6$ are all larger in magnitude than the coefficient estimate, meaning that the t-ratios are very small. This implies that while trading intensity appears to fluctuate around scheduled news announcement events, there is no evidence to suggest that the degree to which the market is surprised by the announcement impacts on the time between trades. Furthermore, Table 9 presents diagnostic statistics for (4) suggesting that (4) may be a less than adequate conditional characterisation of x_i^* as compared with (3).

5 Expected Durations

Using the results from our preferred model with workup and news terms given in (3), an estimate of the expected trade duration under various scenarios can be derived, and are reported in Table 10. The baseline estimate is the expected duration between transactions with no workup occurring at times other than 8:30-9:30 on a non-news announcement day. This can be calculated as

$$E\left(x_i^*\right) = \frac{\mu}{1 - \left(\sum_{j=1}^{5} \gamma_j + \sum_{j=1}^{5} \omega_j \right)} \tag{5}$$

At 1.8187 seconds the baseline expected duration between trades is shortest for the 2 year maturity. The expected durations are longer for the longer maturities but interestingly the expected duration between trades for the 10 year maturity is less than the expected duration for the 5 year maturity. The 30 year maturity displays the highest expected trade duration of 8.12 seconds.

The expected duration occurring between 8:30 and 9:30 am on news announcement days is given by

$$E^N(x_i^*) = \frac{(\mu + \beta_1 + \beta_2)}{1 - \left(\sum_{j=1}^5 \gamma_j + \sum_{j=1}^5 \omega_j + \sum_{j=1}^5 \lambda_j\right)}, \tag{6}$$

and this turns out to be longer than the benchmark for all maturities. Given that $\hat{\beta}_1$ and/or $\hat{\beta}_2$ are statistically significant for the 2 and 30 year maturities this implies that the differences between $E(x_i^*)$ and $E^N(x_i^*)$ are significant.

The expected duration with workup on non-news days, given by

$$E^W(x_i^*) = \frac{(\omega + \beta_3 + \beta_4)}{\left(1 - \left(\sum_{j=1}^5 \gamma_j + \sum_{j=1}^5 \omega_j + \sum_{j=1}^5 \lambda_j\right)\right)} \tag{7}$$

is, in contrast, shorter than the benchmark for all maturities. Table 10 shows that expected durations following workups are 37% (5 year maturity), 27% (10 year maturity) and 45% (30 year maturity) of the corresponding baseline values. Given that the null hypothesis $H_0^4 : \beta_3 = \beta_4 = \beta_5 = 0$ is rejected for all maturities at all usual levels of confidence, we can conclude that the workup of volume in the previous transaction of a given maturity is associated with a shorter duration to the current transaction. Accounting for the information induced by the workup process results in a substantial decrease in the estimated expected adjusted duration.

In the case of news, announcement times and workup the expected duration is given by

$$E^{NW}(x_i^*) = \frac{\left(\omega + \sum_{j=1}^5 \beta_j\right)}{\left(1 - \left(\sum_{j=1}^5 \gamma_j + \sum_{j=1}^5 \omega_j + \sum_{j=1}^5 \lambda_j\right)\right)}. \tag{8}$$

The dominance of the workup effect over the announcement period effect is evident in all but the 2 year maturity. In that case the statistically insignificant point estimate of the presence of workups β_3 does not act in the same direction as for other maturities. For the 5 and 10 year maturities the expected durations with all effects accounted for are shorter than the benchmark, reflecting the importance of workup in understanding trade intensity in these instruments.

The results of the battery of tests and estimations undertaken in this paper strongly support the hypothesis that the trade duration in the US Treasury market is characterised by a relatively high degree of clustering, necessitating longer lag lengths in the

ACD specification than in previously studied markets. Additionally, consistent with existing work on the impact of news announcements on other aspects of the bond market, such as jumps and price impact, trade duration is significantly affected by the presence of news. The evidence suggests that trade intensity is not statistically significantly determined by the extent of news surprises. In this case the presence of news tends to shorten the expected duration between trades. In a new addition to the literature, we also quantify the impact of the workup process on the trade duration. The expandable limit order book is a unique feature of this market, and we find that both the presence and length of workup reduce trade durations in US Treasuries. This provides an important empirical evaluation of the untested hypotheses of Boni and Leach (2004) and Green (2004).

6 Conclusion

This paper focuses on modelling the trading process in the US bond market. Unlike other asset markets, the US Treasury market operates under an expandable limit order book. The unique microstructure of this market raises an interesting question about the role of workup as a important conduit of information that may impact on the trading process. Further, this market is also distinguished by the importance of regularly scheduled macroeconomic news announcements, which have been shown to impact on the bond market. In this paper, we consider the role of both workup and news announcements when modelling the time between transactions in the US Treasury market.

The results of our analysis suggest that the duration between trades for US Treasuries displays a number of unique properties. First, bond markets require a model with much longer lag specifications than other markets; a WACD(5,5) specification provided a superior fit to a first order lag model. Second, news effects are shown to be an important variable for the period immediately surrounding scheduled news release times, although the extent of surprise in the news has no significant effect. Finally, the length of time taken to complete a given transaction has a measurable impact on the time between transactions. A long time to complete tends to be associated with a shorter time to the next transaction. This feature turns out to have a greater impact on reducing the expected adjusted duration than that of the presence of news announcements, and suggests that the microstructure of the market has an important impact on its functioning during times of particularly high activity. These results have implications for our understanding of how bond markets work and the construction of theoretical models of the behaviour of market participants. The results add to our body of understanding of the impact of market architecture on market behaviour, something of value to those emerging markets attempting to initiate bond trading platforms.

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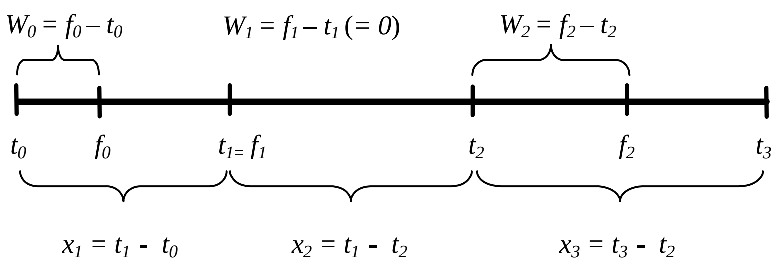

Figure 1: Stylised Representation of the Bond Trading Process

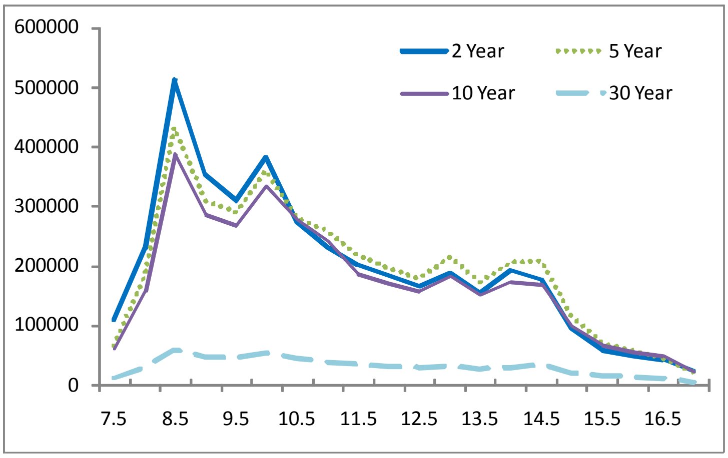

Figure 2: Average Total Trading Volume in a day ($USmil) by half hour interval for each maturity in the period 7:30 am to 5:30 pm for January 3, 2006 to October 6, 2006 inclusive.

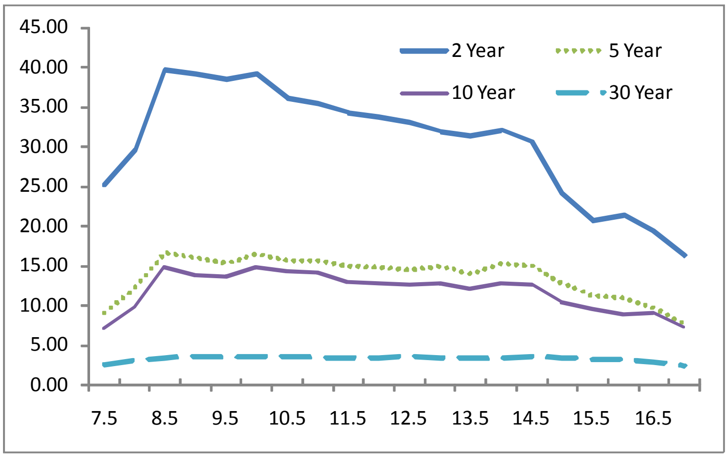

Figure 3: Average Trade Size in $USmillion in a day by half hour interval for each maturity in the period 7:30 am to 5:30 pm for January 3, 2006 to October 6, 2006 inclusive.

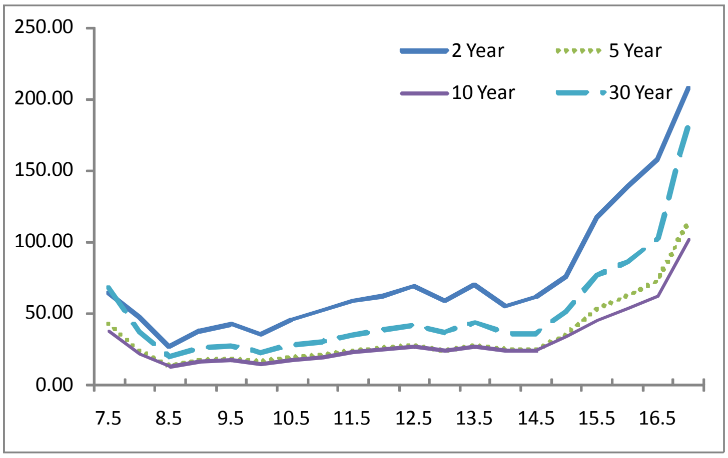

Figure 4: Average Duration in Seconds by half hour intervals in a day for each maturity in the period 7:30 am to 5:30 pm for January 3, 2006 to October 6, 2006 inclusive.

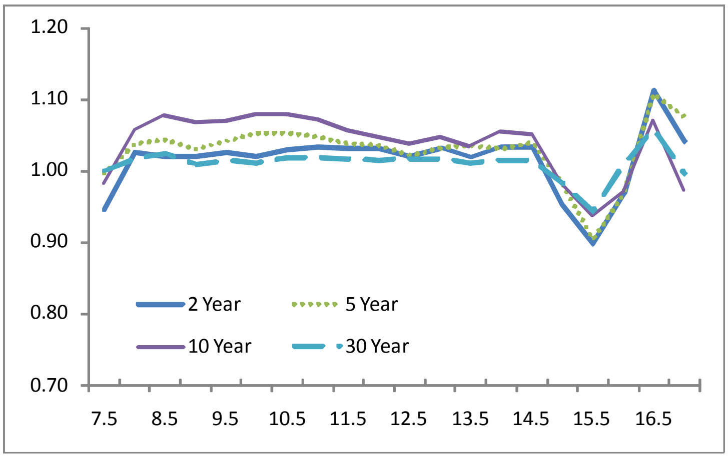

Figure 5: Average Adjusted Duration by half hour intervals in a day for each maturity in the period 7:30 am to 5:30 pm for January 3, 2006 to October 6, 2006 inclusive.

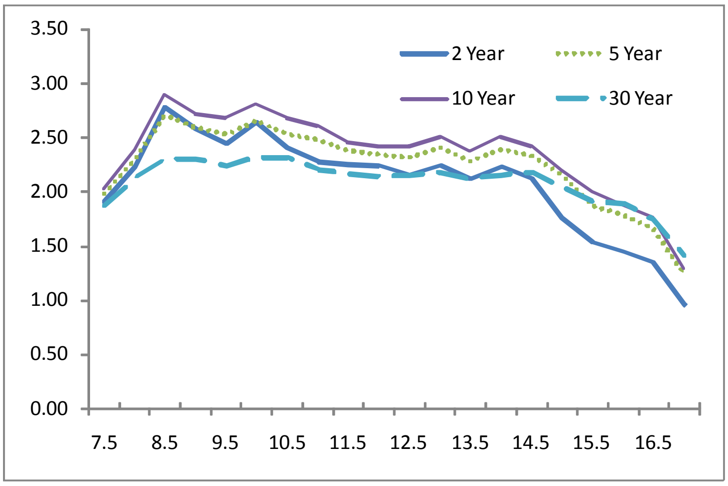

Figure 6: Average Workup Time in Seconds by half hour intervals in a day for each maturity in the period 7:30 am to 5:30 pm for January 3, 2006 to October 6, 2006 inclusive.

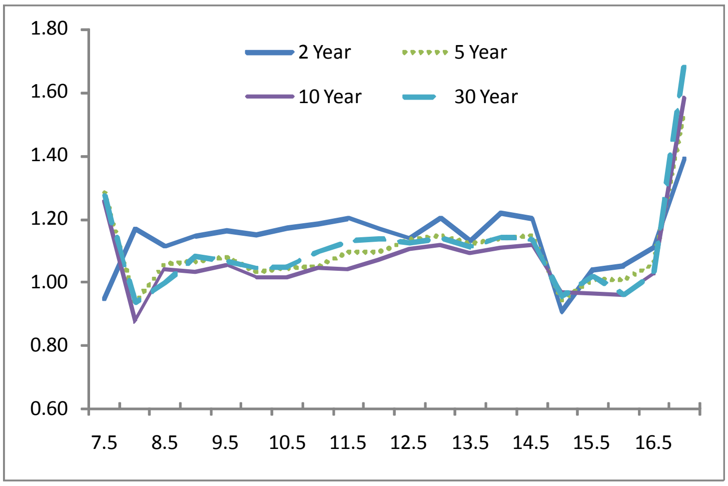

Figure 7: Average Adjusted Workup Time by half hour intervals in a day for each maturity in the period 7:30 am to 5:30 pm for January 3, 2006 to October 6, 2006 inclusive.

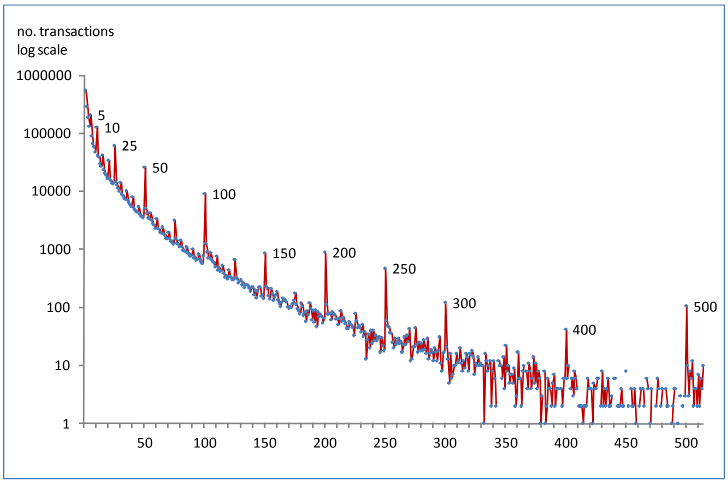

Figure 8: Number of transactions in the 2,5,10 and 30 year maturities transacted by volume of transaction in \$USmil, using a logarithmic vertical scale.

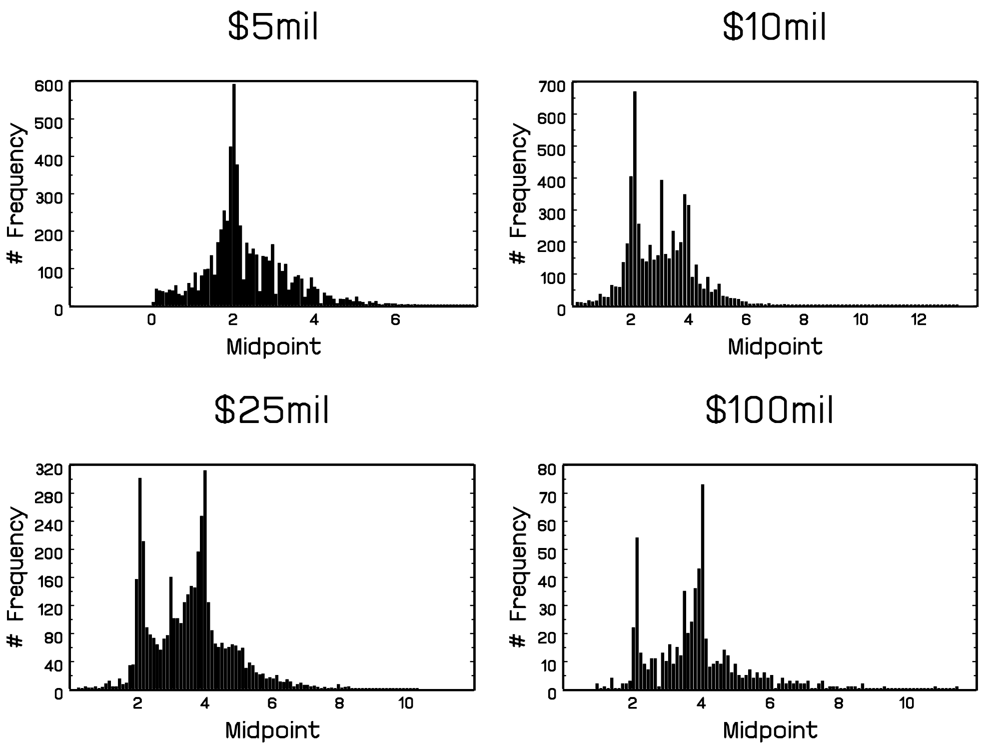

Figure 9: The distribution of workup times for transactions of a given size in the 5 year maturity for the sample period.

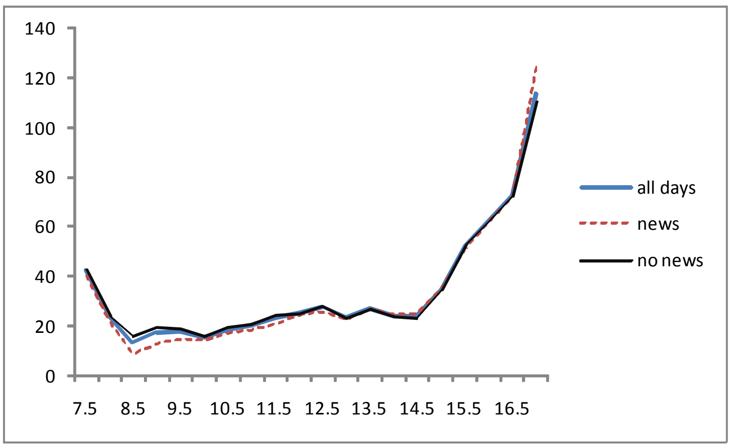

Figure 10: Average duration in seconds for 5 year maturity transactions on all days, news days and no-news days by half hour period.

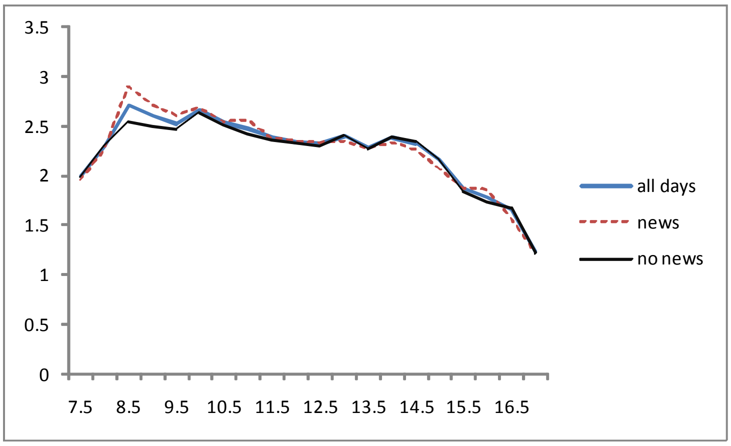

Figure 11: Average workup time in seconds for transactions in 5 year maturity bond for all days, news days and no news days by half hour period.

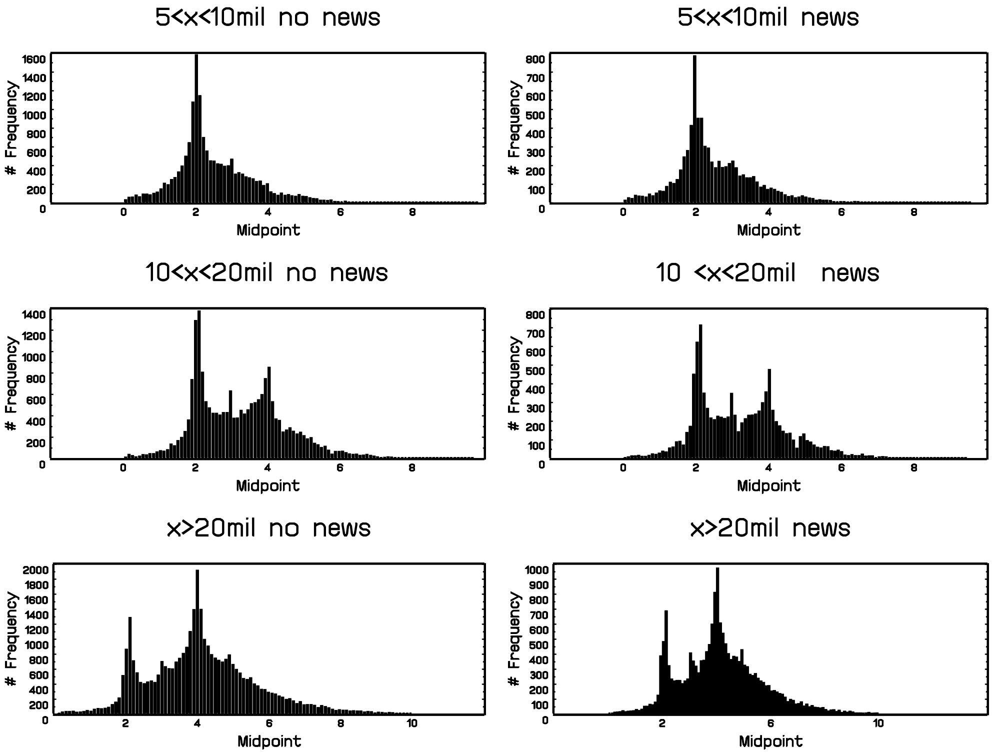

Figure 12: Distribution of workup times for 5 year maturity US Treasury bonds (excluding those with no workup) on no news days and news days by size of transaction in $USmil.

Table 1:
Descriptive statistics of the average trading day for January to September 2006 by maturity

		2 year	5 year	10 year	30 year
Average trades per day		623	1417	1465	951
Size of trade ($USm)	average	33.50	14.56	12.68	3.35
	max	982	641	464	114
	min	1	1	1	1
Workups per day		1128	2976	3101	1494
Duration (seconds)	average	55.86	24.80	24.04	36.53
	max	3545.35	1614.46	1883.37	2163.12
	min	0.006	0.006	0.006	0.001
Duration (diurnalised)	average	1.14	1.10	1.10	1.10
	max	56.89	57.02	64.96	45.12
	min	0.00	0.00	0.00	0.00
Workup (seconds)	average	2.27	2.39	2.51	2.17
	max	36.30	140.01	25.20	137.58
	min	0.00	0.00	0.00	0.00
Workup (diurnalised)	average	1.02	1.02	1.02	1.10
	max	16.79	58.05	16.51	45.12
	min	0.00	0.00	0.00	0.00

Table 2:
Summary statistics for the diurnalised durations, x_i^*.

	2 year	5 year	10 year	30 year
n	116,479	264,902	273,898	177,770
μ	1.1414	1.0967	1.0951	1.0951
	[0.0000]	[0.0000]	[0.0000]	[0.0000]
σ^2	5.3739	2.6412	2.7170	2.6130
$Q(10)$	6176.3812	20688.621	19466.9705	3348.7136
	[0.0000]	[0.0000]	[0.0000]	[0.0000]
$Q(20)$	7792.5831	32684.767	31190.6821	35793.7004
	[0.0000]	[0.0000]	[0.0000]	[0.0000]
$Q(30)$	8844.726	41826.372	39487.8677	44018.4993
	[0.0000]	[0.0000]	[0.0000]	[0.0000]

$Q(p)$ is a Ljung-Box test for p^{th} order correlation.

Table 3:
Descriptive statistics for transactions with and without workup by maturity for January to September 2006.

	2 year	5 year	10 year	30 year
Transactions with no workup				
Proportion of total trades (%)	63.4	53.9	54.8	64.0
Average size of trade ($USm)	18.22	6.35	5.80	2.00
Transactions with workup				
Average workup time	3.59	3.36	3.58	2.97
Volume of trade discovered with workup (%)	65.5	76.5	74.9	61.8

Table 4:
WACD(1,1) model estimates by maturity. [10]

$$x_i = \psi_i \varepsilon_i$$
$$\psi_i = \omega_0 + \gamma_1 x_{i-1} + \omega_1 \psi_{i-1}$$

	2 year	5 year	10 year	30 year
ω_0	0.0657	0.0143	0.0140	0.0211
	(0.0095)	(0.0012)	(0.0008)	(0.0010)
γ_1	0.0960	0.0575	0.0567	0.0846
	(0.0082)	(0.0024)	(0.0016)	(0.0021)
ω_1	0.8414	0.9299	0.9310	0.8969
	(0.0168)	(0.0031)	(0.0020)	(0.0027)
α	0.7255	0.9752	0.9555	0.9026
	(0.0016)	(0.0024)	(0.0014)	(0.0016)
$Q(10)$	509.1707	121.6699	609.7800	250.9219
	[0.0000]	[0.0000]	[0.0000]	[0.0000]
$Q(20)$	523.8488	691.4006	174.3761	327.5845
	[0.0000]	[0.0000]	[0.0000]	[0.0000]
$Q(30)$	560.9178	174.3761	735.9692	343.5661
	[0.0000]	[0.0000]	[0.0000]	[0.0000]
$Q^2(10)$	73.7984	16.6681	48.2440	39.0051
	[0.0000]	[0.0822]	[0.0000]	[0.0000]
$Q^2(20)$	97.0448	28.5084	66.5963	53.9125
	[0.0000]	[0.0964]	[0.0000]	[0.0000]
$Q^2(30)$	153.1990	56.8736	86.8946	59.0098
	[0.0000]	[0.0022]	[0.0000]	[0.0012]
$E(x_i)$	1.0495	1.1349	1.1382	0.4637
$\rho(x_i)$	0.9374	0.9874	0.9877	0.9545

Notes: α is the shape parameter in the Weibull distribution. $Q(p)$ and $Q^2(p)$ are tests for p^{th} order serial correlation in ε_i and ε_i^2, respectively. Standard errors are displayed as (.). Marginal significance levels are displayed as [.].
$E(x_i) = \omega_0 / (1 - (\gamma_1 + \omega_1))$ is the expected adjusted duration. The expected persistence of the adjusted durations is $\rho(x_i) = \gamma_1 + \omega_1$.

Table 5:
WACD(5,5) model estimates by maturity.[11]

$$x_i = \psi_i \varepsilon_i$$
$$\psi_i = \omega_i + \sum_{j=1}^{5} \gamma_j x_{i-j} + \sum_{j=1}^{5} \omega_j \psi_{i-j}$$

	2 year	5 year	10 year	30 year
ω_0	0.0439	0.0373	0.0343	0.0017
	(0.0033)	(0.0023)	(0.0020)	(0.0023)
$\sum_{j=1}^{5} \gamma_j$	0.1497	0.2702	0.2389	0.0608
	(0.0061)	(0.0085)	(0.0064)	(0.0098)
$\sum_{j=1}^{5} \omega_j$	0.7934	0.6852	0.7186	0.9291
	(0.0087)	(0.0100)	(0.0077)	(0.0117)
α	0.7292	0.9564	0.9561	0.9043
	(0.0018)	(0.0014)	(0.0014)	(0.0013)
$Q(10)$	20.4096	52.5600	65.389	23.373
	[0.0011]	[0.0000]	[0.0000]	[0.0095]
$Q(20)$	39.4280	96.9730	85.223	34.294
	[0.0059]	[0.0000]	[0.0000]	[0.0242]
$Q(30)$	62.5230	119.150	118.910	53.980
	[0.0005]	[0.0000]	[0.0000]	[0.0046]
$Q^2(10)$	57.743	29.4960	36.609	38.041
	[0.0000]	[0.0010]	[0.0001]	[0.0000]
$Q^2(20)$	73.860	69.510	68.382	64.375
	[0.0000]	[0.0000]	[0.0000]	[0.0000]
$Q^2(30)$	86.552	107.593	89.005	71.142
	[0.0000]	[0.0000]	[0.0000]	[0.0000]
$E(x_i)$	0.7715	0.8363	0.8071	1.1584
$\rho(x_i)$	0.9431	0.9554	0.9575	0.9899

Notes: α is the shape parameter in the Weibull distribution. $Q(p)$ and $Q^2(p)$ are tests for p^{th} order serial correlation in ε_i and ε_i^2, respectively. Standard errors are displayed as (.). Marginal significance levels are displayed as [.].
$E(x_i) = \mu / \left(1 - \left(\sum_{j=1}^{5} \gamma_j + \sum_{j=1}^{5} \omega_j\right)\right)$ is the expected adjusted duration. The expected persistence of the adjusted durations is $\rho(x_i) = \sum_{j=1}^{5} \gamma_j + \sum_{j=1}^{5} \omega_j$

Table 6:
Threshold WACD(5,5) estimates.

	2 year	5 year	10 year	30 year
μ	0.0482	0.0483	0.0522	0.0658
	(0.0081)	(0.0059)	(0.0063)	(0.0054)
β_1	-0.0023	-0.0002	-0.0008	0.0003
	(0.0008)	(0.0004)	(0.0004)	(0.0004)
β_2	-0.0363	0.0006	0.0001	0.0030
	(0.0557)	(0.0015)	(0.0015)	(0.0013)
β_3	0.0022	-0.0025	-0.0023	-0.0073
	(0.0058)	(0.0010)	(0.0010)	(0.0011)
β_4	-0.0218	-0.0239	-0.0248	-0.0454
	(0.0022)	(0.0054)	(0.0057)	(0.0049)
β_5	0.0271	-0.0091	-0.0133	-0.0043
	(0.0470)	(0.0009)	(0.0008)	(0.0008)
$\sum_{j=1}^{5} \gamma_j$	0.0490	0.0336	0.0371	0.0701
	(0.0043)	(0.0013)	(0.0016)	(0.0037)
$\sum_{j=1}^{5} \omega_j$	0.9244	0.9586	0.9498	0.9218
	(0.0071)	(0.0018)	(0.0023)	(0.0047)
$\sum_{j=1}^{5} \lambda_j$	0.0173	0.0021	0.0027	0.0048
	(0.0030)	(0.0016)	(0.0014)	(0.0013)
α	0.7319	0.9604	0.9607	0.9055
	(0.0017)	(0.0034)	(0.0015)	(0.0016)

Notes: α is the shape parameter in the Weibull distribution. Standard errors are displayed as (.).

Table 7:
Hypothesis tests and diagnostic statistics for the Threshold WACD(5,5).

	2 year	5 year	10 year	30 year
$Q(10)$	13.351	14.906	8.251	11.991
	[0.2047]	[0.1355]	[0.6043]	[0.2587]
$Q\,(20)$	27.137	31.353	18.548	24.546
	[0.1315]	[0.0507]	[0.5572]	[0.2193]
	Hypothesis Tests			
H_0^1 :WACD	132.5719	126.930	273.4498	21.2908
$\tilde{}\chi^2\,(10)$	[0.0000]	[0.0000]	[0.0000]	[0.0192]
$H_0^2 : \beta_3 = 0$	0.3793	-2.5000	-2.3000	-6.6364
	[0.7045]	[0.0124]	[0.0214]	[0.0000]
$H_0^3 : \beta_4 = 0$	-9.9091	-4.4259	-4.3059	-9.2653
	[0.0000]	[0.0000]	[0.0000]	[0.0000]
$H_0^4 : \beta_3 = \beta_4 = \beta_5 = 0$	98.8932	103.2824	227.0574	16.6068
$\tilde{}\chi^2\,(3)$	[0.0000]	[0.0000]	[0.0000]	[0.0000]
$H_0^5 : \beta_1 = 0$	-2.8750	-0.5000	-2.0000	0.7500
	[0.0040]	[0.6171]	[0.0455]	[0.4533]
$H_0^6 : \beta_1 = \beta_2 = \lambda_j = 0$	43.1907	12.9482	16.3875	7.0662
$\tilde{}\chi^2\,(7)$	[0.0000]	[0.0734]	[0.0000]	[0.0422]

Notes: $Q\,(p)$ is a test for p^{th} order serial correlation in ε_i. Marginal significance levels are displayed as $[.]$.

Table 8:
Threshold WACD(5,5) estimates with standardised surprises.

	2 year	5 year	10 year	30 year
μ	0.0419	0.0626	0.0829	0.0487
	(0.0123)	(0.0094)	(0.0018)	(0.0105)
β_1	-0.0016	-0.0008	-0.0016	-0.0006
	(0.0011)	(0.0003)	(0.0004)	(0.0005)
β_2	0.0679	-0.0212	-0.0400	0.0087
	(0.0322)	(0.0193)	(0.0054)	(0.0168)
β_3	-0.0012	-0.0386	-0.0455	-0.0325
	(0.0092)	(0.0085)	(0.0023)	(0.0085)
β_4	-0.0176	-0.0113	-0.0178	-0.0039
	(0.0317)	(0.0009)	(0.0007)	(0.0014)
β_5	-0.0697	0.0187	0.0362	-0.0116
	(0.0320)	(0.0193)	(0.0054)	(0.0168)
β_6	-0.0003	-0.0002	-0.0002	-0.0001
	(0.0008)	(0.0003)	(0.0003)	(0.0003)
$\sum_{j=1}^{5}\gamma_j$	0.0398	0.0430	0.0527	0.0525
	(0.0061)	(0.0037)	(0.0016)	(0.0077)
$\sum_{j=1}^{5}\omega_j$	0.9374	0.9450	0.9287	0.9349
	(0.0105)	(0.0048)	(0.0021)	(0.0098)
$\sum_{j=1}^{5}\lambda_j$	0.0075	0.0047	0.0067	0.0060
	(0.0039)	(0.0014)	(0.0018)	(0.0018)
α	0.7317	0.9603	0.9614	0.9054
	(0.0014)	(0.0010)	(0.0012)	(0.0014)

Notes: α is the shape parameter in the Weibull distribution. Standard errors are displayed as (.).

Table 9:
Diagnostic statistics for the Threshold WACD(5,5) with standardised surprises.

	2 year	5 year	10 year	30 year
$Q(10)$	17.126	41.855	19.515	17.450
	[0.0716]	[0.0000]	[0.0342]	[0.0650]
$Q\,(20)$	30.124	66.959	28.266	30.212
	[0.0678]	[0.0000]	[0.1033]	[0.0665]

Notes: $Q\,(p)$ is a test for p^{th} order serial correlation in ε_i. Marginal significance levels are displayed as $[.]$.

Table 10:
Expected Durations from the Threshold WACD(5,5).

	2 year	5 year	10 year	30 year
$E(x_i)$	1.8120	6.1923	3.9847	8.1235
$E^N(x_i)$	1.0323	8.5436	4.9519	20.8485
$E^W(x_i)$	1.0752	2.8077	1.9160	1.6173
$E^{NW}(x_i)$	1.8387	2.3158	1.0674	3.6667
$\rho(x_i)$	0.9874	0.9922	0.9869	0.9919
$\rho^N(x_i)$	0.9907	0.9943	0.9896	0.9967

Notes: $E(x_i)$is the expected adjusted duration. The expected persistence of the adjusted durations is $\rho(x_i)$.

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