

Fleming, Michael; Nguyen, Giang

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## Order flow segmentation and the role of dark trading in the price discovery of U.S. treasury securities

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Federal Reserve Bank of New York  
Staff Reports

# Order Flow Segmentation and the Role of Dark Trading in the Price Discovery of U.S. Treasury Securities

Michael Fleming  
Giang Nguyen

Staff Report No. 624  
August 2013



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# **Order Flow Segmentation and the Role of Dark Trading in the Price Discovery of U.S. Treasury Securities**

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## **Abstract**

This paper studies the workup protocol, a unique trading feature in the U.S. Treasury securities market that resembles a mechanism for discovering dark liquidity. We quantify its role in the price formation process in a model of the dynamics of price and segmented order flow induced by the protocol. We find that the dark liquidity pool generally contains less information than its transparent counterpart, but that its role is not trivial. We also show that workups are used more often around volatile times, but that their information role becomes relatively less important at those times compared to that of pre-workup trades. Higher usage of workups is also associated with higher market depth, lower bid-ask spreads, and higher trading intensity. Collectively, the evidence suggests that workups tend to be used more as a channel for liquidity providers to guard against adverse price movements than as a channel to hide private information.

Key words: dark pool, liquidity, price impact, information share, fixed-income market

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Fleming: Federal Reserve Bank of New York (e-mail: michael.fleming@ny.frb.org). Nguyen: University of North Carolina at Chapel Hill (e-mail: gnguyen@email.unc.edu). The authors thank Weiling Liu for excellent research assistance. The views expressed in this paper are those of the authors and do not necessarily reflect the position of the Federal Reserve Bank of New York or the Federal Reserve System.

# 1 Introduction

The ability to hide trading intention is important and valuable to market participants. As [Harris \(1997\)](#) writes: “the art of trading lies in knowing when and how to expose trading interest.” Many trading venues provide features that enable market participants to manage their exposure, ranging from hidden orders to dark pools.

The BrokerTec platform, one of two interdealer electronic trading platforms for U.S. Treasury securities, is one such place where traders can conceal the extent of their trading interest. One way they can do this is through iceberg orders. An iceberg order is a limit order that displays only a portion of the order quantity, called the display size, with the rest invisible to the market. The hidden quantity is revealed only gradually to the market as the displayed size is fully executed and the next installment becomes visible.

A second way traders can conceal the extent of their trading interest is through the workup process. A workup is a protocol that automatically opens after the execution of each market order. During the workup window, any interested market participants can transact additional volume at the same price established by the initial execution, as long as counter trading interest exists. Workups thus provide traders the option to submit orders of smaller size than desired, and then to increase the size when the workup opportunity opens.

It is intriguing to observe that, in this market, iceberg orders are used sparingly compared to workups, even though the former has higher execution priority. On average, less than 5% of transactions involve execution against iceberg orders, whereas volume expansion through the workup protocol happens 49–56% of the time for the on-the-run 2-, 5- and 10-year notes and nearly 40% of the time for the 30-year bond.

The economic significance of the workup protocol is demonstrated not only by its frequent usage, but also by the magnitude of the expanded volume. On a typical day, worked-up trading volume accounts for about 43–56% of total trading volume, depending on the security being traded. In a typical transaction with a workup, the worked-up dollar volume accounts for over 60% of total volume. Collectively, these statistics show that the workup protocol

uncovers a significant amount of market liquidity that is not ex ante observable to market participants. More importantly, the workup feature relates to a salient fact about the Treasury limit order book: market orders rarely walk up or down the book, at least for the on-the-run securities examined in this paper.

The fact that a significant portion of market liquidity is only revealed during the workup process raises an important question about its role in the price formation process. Does this portion of order flow carry information? If so, how does it compare to the “transparent” part (i.e., the execution of the initiating market order)? Up until now, the literature on price discovery of U.S. Treasury securities, such as [Brandt and Kavajecz \(2004\)](#), [Green \(2004\)](#), [Pasquariello and Vega \(2007\)](#), and others, has been concerned only with the informational role of generic order flow. Implicitly, it is assumed that the trade flow is homogeneous and that the portion transacted in the pre-workup stage has the same impact on price dynamics as the portion transacted in the workup phase.

The theoretical literature on dark trading suggests that this is not the case. For example, [Zhu \(2012\)](#) argues that the different execution probability of orders in transparent versus dark venues for the informed versus uninformed traders likely steers informed traders to the transparent venue and uninformed traders to the dark venue. In contrast, [Ye \(2012\)](#) predicts that informed traders are more likely to hide their information in the dark, thereby reducing price discovery. Although arriving at opposing predictions, both models suggest that the information content of the transparent and dark parts of trading is different as a result of how informed traders optimize their exposure strategy to exploit their information advantage.

It is also not realistic to study the information role of trades in this market without recognizing or appreciating that the workup feature is an integral part of the trading process and a useful device for order exposure management. Accordingly, it can alter traders’ optimization outcomes and decisions, as compared to a hypothetical market setup in which this option is not available. For example, aside from choosing between market and limit orders, traders also have choices over the exposure of their trading intention. If it is a limit

order, the submitter can 1) display the full order size, 2) submit the full order size but hide part of it from view (i.e., submit an iceberg order), or 3) submit a smaller sized order and wait to expand the order size when the order is executed and the workup process is open. Likewise, if it is an aggressive order, the available choices are: 1) submit the full sized market order for immediate execution, 2) submit a smaller sized market order and hope to increase the volume in the ensuing workup, or 3) wait for a workup at the right price to trade. The fact that workups are used so frequently in this market speaks for its importance in traders' decision making.

The workup protocol, by providing traders with an option to expand order size beyond the initially submitted level, can be beneficial to the informed traders in multiple ways. For example, an informed trader may choose to submit a limit order of less than the intended quantity to minimize information free-riding by others, knowing that he has the opportunity to increase the size when the order is aggressed against (i.e., executed by a market order). These are the “informed liquidity providers” as discussed in [Boulatov and George \(2013\)](#). Alternatively, an impatient informed trader with a large trading interest may submit a market order small enough to execute at the best price, and then search for further counter trading interest during the subsequent workup at the same price, without having to walk deeper into the book.

The informativeness of the workup order flow, however, also depends on the actions of the uninformed. If they behave in the sense of [Zhu \(2012\)](#), or if they are reactive traders who act upon the lead of others as described in [Harris \(1997\)](#), the uninformed are more likely to trade in the workup stage, thereby reducing the informativeness of workup order flow. Likewise, the uninformed can participate in the market on the liquidity provision side, and thus volume expansion of limit orders during workups is not necessarily information motivated.

Given the mixed guidance from theory, the informativeness of workup order flow in practice is an open question. The paper aims to address this question and thereby provide a more complete picture of the price formation process of U.S. Treasury securities. We do

this by separating order flow into the trade initiation part (or the “transparent” part) and the workup part (or the “dark” part), and quantifying how these respective components contribute to the variation in the random walk component of the efficient price.

Based on transaction data for the on-the-run 2-, 5-, 10- and 30-year Treasury securities from the BrokerTec platform over the period 2006–2011, we find that workup order flow is informative, albeit less informative than trade initiation order flow. Workup order flow is most informative for the 2-year note, explaining about 17% of the total variation of the efficient price updates. The 5- and 10-year counterparts explain between 7–8% of the variation of the efficient price. It is only 1%, however, for the 30-year bond, indicating that traders in this maturity segment do not opt for the workup as a channel to exploit their information advantage. Price discovery in the 30-year segment is most attributable to public information – which accounts for over 80% of the variation of the efficient price innovations. Our analysis also illustrates the importance of recognizing the information segmentation of order flow due to the workup protocol by showing that the impact of actively initiating a trade and the share of trade-related information are underestimated if one does not consider the segmentation.

Except for the 2-year note where the workup order flow is slightly more informative, our information share analysis generally supports the predictions by [Zhu \(2012\)](#) in that the transparent part of order flow is much more informative than the dark part. Our evidence is also consistent with [Comerton-Forde and Putnins \(2013\)](#) who study dark trading and price discovery of stocks traded on the Australian Stock Exchange and find that the order flow that migrates to the dark is less informed, but not completely uninformed. Intuitively, informed traders with a short-lived information advantage may choose to initiate a trade and realize their information advantage quickly, since the potential of not finding a counterparty during the workup can make the workup option costly (e.g., forgone information value). This is strongly supported by our result that the transparent (or “lit”) part of the order flow becomes relatively more informationally important on high volatility days, when adverse price movements could fasten the expiry of information.

Although less informative than the trade initiation flow, the workup process is responsible for the discovery of a significant portion of market liquidity and plays a non-trivial role in the updating of the efficient price. It is therefore important to understand what factors might predict the use of a workup following a market order execution and the extent of the volume expansion. We employ a logistic regression model for the probability of a workup as a function of hypothesized determinants, including prevailing order book depth on the same side, spread, depth on the other side, price volatility and a set of control variables. We employ a Tobit model censored at the lower bound of zero to capture the effects of the same set of explanatory variables on workup volume, since volume is zero for non-workup transactions and strictly positive for those with a workup. We find that, in general, a workup is more likely and expands greater volume when the market is deep, upon the discovery of hidden orders, and around the times of high trading intensity, volatility and workup activity. Outside New York trading hours, workups are used less frequently and also discover less volume.

Despite workups being a unique and economically important trading feature in the U.S. Treasury market, academic research specifically on the workup process and its implications on market participants' trading strategies is limited. The paper closest to ours is [Boni and Leach \(2004\)](#) who investigate the workup protocol using GovPX data for October 1997. At that time, interdealer trading was still conducted over a network of voice-assisted interdealer brokers (IDB). GovPX collected and disseminated market data from five such IDBs. Each of the IDBs maintained its own limit order book, facilitated trades and mediated quantity negotiations beyond the quoted depth. [Boni and Leach](#) hence characterize this market as one in which limit orders are “expandable”.<sup>1</sup> They find that this expandability option helps limit

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<sup>1</sup>BrokerTec's workup protocol differs from that of voice-assisted brokers in several ways. First, quantity negotiation on BrokerTec is governed by a set of precise rules stipulating the window of opportunity for workup trades, replacing the role of human brokers in going back and forth between counterparties working up the size of a trade. Second, as explained by [Boni and Leach](#), with the voice-assisted brokers, when a limit order on an IDB's book is aggressed by a market order, the IDB gives the limit order's submitter the right-of-first-refusal to provide additional liquidity, even when there are other limit orders at the same price in the book. This exclusivity was completely eliminated on BrokerTec in early 2006, making workups immediately open to all market participants following the original trade(s) on a first come, first serve basis



order traders reduce costs associated with information leakage and adverse execution of stale limit orders.

Dungey, Henry, and McKenzie (2013) account explicitly for the workup feature in their model of trading intensity on eSpeed, the other electronic trading platform. They find that the duration of a workup significantly fastens the arrival of the next market order. They interpret this result in light of the theory by Easley and O'Hara (1992) that market participants infer the presence of informed traders by the time between trading events. They thus suggest that a workup provides information to the market.

Adding to this literature, our paper is the first to consider the segmented order flow due to the workup protocol and formally quantify the informativeness of the dark trade flow in comparison with that of the transparent trade flow in a well defined microstructure model of the dynamics of price and order flow. The paper therefore provides a more complete picture of how the trading process with the embedded workup feature – a unique microstructure feature of secondary trading in U.S. Treasury securities – affects the price formation process of these securities.

Furthermore, we extend the model used by Boni and Leach by exploring and controlling for a wider range of potential determinants of workups as suggested by the literature on dark pool trading and hidden liquidity. The extension is also valuable because the workup protocol as prevailing on BrokerTec differs considerably from its historical precedent as studied in Boni and Leach, making it important to keep our understanding of market functioning up to date.

Our contribution goes beyond a study of a specific microstructure feature of the U.S. Treasury market. The workup process resembles a crossing network, a common form of dark

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(source: “System and Method for Providing Workup Trading without Exclusive Trading Privileges”, patent number US 8,005,745 B1, dated August 23, 2011). Furthermore, the expanded volume can come from either the aggressive or passive side during a workup so that the workup is no longer confined to expanding only limit orders. Most recently, BrokerTec instituted a new rule that allows for a workup to terminate prematurely if there is sufficient trading interest at a better price point to facilitate the faster speed of trading driven by the rise of computer algorithms (source: “System and Method for Providing Workup Trading”, patent number US 7,831,504 B1, dated November 9, 2010).

pool used in many equity trading venues.<sup>2</sup> The paper is a timely addition to the literature on crossing networks – and dark trading in general – where evidence pertaining to the Treasury market is limited, and where there is currently an active debate on the effects and implications of dark pool activities on market quality and welfare. On the one hand, the existence of undisplayed liquidity compromises pre-trade transparency and can potentially disadvantage less informed traders. On the other hand, supporters of dark pool trading mechanisms point to greater market liquidity and better execution quality for trades, especially for large trades that can be executed without causing negative price impact. Complicating matters, dark pools come in many forms. It is therefore important to understand these various types of dark pools in different market setups and how their specific operationalization might affect trading behavior and patterns.

The paper is organized as follows. Section 2 describes the workup process in detail, discusses the data used for the analysis and presents key stylized facts concerning workups. Section 3 presents a microstructure model for the dynamics of segmented order flow and price, and analyzes the price impact and informativeness of the respective components of order flow. In Section 4, we model and discuss the dependence of workup probability and workup volume on market condition variables. Finally, Section 5 summarizes our key empirical findings and concludes the paper.

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<sup>2</sup>Buti, Rindi, and Werner (2011b) characterize dark pools as having “limited or no pre-trade transparency, anonymity and derivative pricing.” The workup process enables execution of additional trading interests not observed by market participants before each transaction. All trades through interdealer brokers in the Treasury market are anonymous. During the allowable time window for a workup, market participants can send in orders, which are then matched by the system. Any unmatched volume is held in the system for potential matching with subsequent contra trading interest later in the workup. The price for these workup executions derives from the execution of the initial market order that triggers the workup. We thank Joel Hasbrouck for this insight.

## 2 The Workup Process

### 2.1 Market Overview

This paper focuses on the interdealer trading segment of the secondary market for U.S. government securities. Trading in this segment, especially in the on-the-run securities, occurs mostly on two electronic trading platforms, BrokerTec and eSpeed (Barclay, Hendershott, and Kotz (2006)). Comparing BrokerTec trading statistics with those reported by other studies using eSpeed data (e.g., Dungey, Henry, and McKenzie (2013) and Luo (2010)), we document a greater market share for BrokerTec across all four securities examined in this study.<sup>3</sup> Dunne, Li, and Sun (2011) compare price discovery on the two platforms using non-contiguous data for 2002, 2004 and 2005 and conclude that more price discovery takes place in the more active but less transparent BrokerTec platform.<sup>4</sup>

Both BrokerTec and eSpeed operate as electronic limit order markets with no designated market maker. Liquidity supply comes from the limit order book, which is a collection of limit orders at various price levels submitted by market participants. Execution of orders follows the price, time and display status priority rule. Our empirical analysis is based on BrokerTec data and our discussion of how the market works is for the BrokerTec platform.

In submitting limit orders, market participants can choose to display either completely or partially the order size. If the latter, the rest of the order size is not observable by other market participants. As the displayed portion is exhausted through trading, the next installment of the order quantity becomes displayed. This process continues until the total order quantity is completely executed. See Fleming and Mizrach (2009) for an analysis of iceberg orders in this market.

Traders demanding liquidity can send in market orders. Market orders must be priced.

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<sup>3</sup>Comparison of BrokerTec and eSpeed activity for the same sample periods and trading hours shows that the market share of BrokerTec ranges between 57% to slightly over 60% for the 2-, 5- and 10-year notes. The market share in the 30-year bond is slightly lower, but it is still over 50%.

<sup>4</sup>These authors note that eSpeed does not have hidden orders, whereas BrokerTec allows such orders and is thus considered as having less pre-trade transparency.

That is, beside the order quantity and whether it is a purchase or sale, traders must specify a price. When a market order arrives, it is matched with one or more limit orders standing on the opposite side at that price (or better), with the displayed depth having higher priority of execution over hidden depth. For example, for a market order to *buy* a quantity  $Q$  at the price  $P$ , the order will be matched with displayed limit *sell* orders at all price points lower than or equal to  $P$ , up to the desired quantity  $Q$  or the total available quantity of these limit sell orders, whichever smaller. If a limit sell order is an iceberg order, upon the execution of the displayed portion, the next portion becomes visible and enters the end of the limit order queue at that price point. It is noted that limit orders on opposite sides with the same price do not automatically match. They can only be matched with market/aggressive orders.

The execution of a market order is just the beginning of a transaction. Once all possible matches have been made (against displayed and then hidden depth in the book, if any), the market then enters into the workup process during which additional volume at the same price can be transacted, until there is no further trading interest. As described in one of BrokerTec’s patent documents relating to the workup protocol, the whole process is conceptually “a single deal extended in time”.<sup>5</sup> The next subsections provide a detailed description of how the workup protocol works and present descriptive analysis of trading and workup activities.

## 2.2 The Workup Process

The workup is a unique feature of trading in U.S. Treasury securities. The process automatically opens after each market order execution, giving all market participants the chance to transact additional quantity at the same price, e.g., at the price  $P$  as in the above example. The ability to transact additional quantity during the workup process thus enables traders to submit orders of smaller size than their desired quantity, and then expand the quantity during the workup. The workup protocol therefore offers a higher degree of control over if and when to trade the additional needed quantity, whereas iceberg orders are subject to

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<sup>5</sup>“System and Method for Providing Workup Trading”, U.S. Patent No. 7,831,504 B1, dated 11/9/2010.

the risk of being adversely executed before the order owners have a chance to modify or cancel. However, the cost for the traders hoping to expand volume in a workup is that the incremental quantity they expect to transact may not materialize if counter trading interest is lacking.

Historically, the workup process consisted of two distinct phases: 1) the private phase, which gave an exclusive right of first refusal to the original parties to the transaction, and 2) the public phase, which is open to all other market participants. However, around 2006, the private phase was replaced by a public phase, making the workup a double-public process. As a result, a transaction will progress straight to the first public workup phase after all possible matches with the limit order book have been completed. During this phase, additional trading interest can come from either side of the market, and these extra trades are conducted on a first come, first serve basis.

The first public workup phase is open for a pre-specified duration (it was 4 seconds from early 2006 until July 2011 when the duration was shorted to 3 seconds). If there is no trading interest, the workup process automatically expires at the end of this duration. However, if and when a new execution occurs during this time window, the second public phase commences and a new duration opens up. It is then re-settable each time a new execution occurs. This protocol allows the workup to last as long as there is trading interest at the same price point, or to terminate after a predetermined time period if no such interest exists so that the market can move forward.

All trades during a workup – triggered by the initial execution of a market order – are executed at the same price as that of the original market order. Since the extra liquidity discovered during the workup process at a given price point is not known to the market *ex ante*, the workup process can be likened to a dark pool trading mechanism, in which the reference price for the execution of workup orders is the price of the initial market order. Accordingly, we treat the whole process from the initial execution to the expiration of the ensuing workup as a single transaction. Each transaction can involve multiple trades or order

matches. For example, a market order can execute against multiple (smaller sized) limit orders. Each of these executions is recorded separately in the database and is referred to as a trade, an order match, or an execution. We refer to those trades (or matches) that happen before the workup as pre-workup trades. Other interchangeable terms for “pre-workup trades” include “transparent trades”, “lit trades”, “normal trades”, and “non-workup trades”. Those that occur during the workup phase are referred to as workup trades or “dark trades”.

## 2.3 The BrokerTec Data

The tick data from BrokerTec contains records of all market activity, from limit order submission, cancellation, and modification to matching with incoming market orders, time-stamped to the millisecond. We extract information on all trading activity from this raw, comprehensive database. There is a flag each time a market order arrives. Once automatic order matching with the limit order book completes, another flag indicates the commencement of the workup phase. Finally, when the workup expires, it is also flagged in the database. As a result, we are able to identify the complete sequence of activities pertaining to each transaction.

The trade direction of the original market order, i.e., whether it is a buy or a sell, is also recorded, thus providing unambiguous signing of all pre-workup trades. Trades matched in the workup process are conducted at the same price point as the original market order. Market practice has traditionally signed such trades (and determined brokerage fees) based on the sign of the originating market order. BrokerTec signs workup trades accordingly and we retain BrokerTec’s assignments for our analysis.

After identifying the sequence of activities for each transaction, we aggregate information for the transaction, separately for the pre-workup and workup phases. In particular, we count the number of trades as well as the total dollar volume exchanged in each respective phase. Furthermore, if there is execution against the displayed portion of an iceberg order resulting in the exposure of new depth, we mark the transaction as involving execution against an

iceberg order.

The transaction data is then combined with the limit order book snapshots prevailing just before and after each transaction. The limit order book is reconstructed from the raw BrokerTec data described above by accumulating changes to the order book from the beginning of each trading day. Combining the limit order book data with the transaction data provides a complete picture of the market at each transaction, facilitating our empirical analysis into factors that are likely related to workup activities.

Our sample covers the period from 2006 to 2011. We focus the study on the on-the-run 2-, 5-, 10- and 30-year securities. The 3- and 7-year notes are excluded from our analysis. Issuance of the 3-year note was suspended between May 2007 and November 2008. Issuance of the 7-year note was suspended between April 1993 and February 2009.

## **2.4 Univariate Analysis of Workup Activities**

### **2.4.1 Trading and Workup Activities**

An overview of market trading activity is presented in Table 1. Panel A shows the average daily total trading volume and number of transactions. The 2-, 5- and 10-year notes have comparable trading volume in the \$30–35 billion range. This far exceeds the average of \$5 billion in daily trading volume for the 30-year bond. The number of transactions per day varies across securities, from the low 1,000’s range for the 2- and 30-year securities to over 2,600 for the 5- and 10-year notes. It follows that trading in the 2-year note often occurs in much larger size than is the case for other securities.

We find that market participants utilize the workup protocol in about 49–56% of transactions for the notes, but only 39% of transactions for the 30-year bond. The workup share of dollar volume is very similar to the share of transactions, except for the 30-year bond whose volume share is slightly higher than the share of transactions, at 43%.

To complement the sample average statistics on workups, we further examine the time series trend of the use of workups in Figure 1. There is a modest increase in the use of

workups from early 2006 until late 2008, when the workup shares of transactions and order flow drop before partially bouncing back in early 2009. The patterns have been fairly stable since then, except for a sharp decline in workups for the 2-year note, to about 40% in the second half of 2011. Also evident from the figure is that workups in the 30-year bond happen less frequently than they do in the notes, but expand proportionally greater volume when they do occur.

Table 1, Panel A also reports the probability of transacting against an iceberg order for comparison, and illustrates that workups are used much more frequently in this market. The chance of hitting/taking an iceberg order is only around 4%, which is less than one tenth the probability of having a workup. Additionally, the workup protocol, in providing traders with the opportunity to expand transaction volume at a given price, possibly contributes to the finding that transactions in these on-the-run Treasuries almost never execute at multiple prices, beside the fact that the market is often very deep relative to the size of most market orders.

Further details at the transaction level, with and without workups, are presented in Panels B and C respectively. We discuss first the transactions with workups (Panel B). This panel shows that the 2-year note has the largest dollar volume per transaction when there is a workup, at about \$42 million. This is more than double the size of a transaction in the 5- or 10-year notes and about eight fold the size of a typical transaction in the 30-year bond. The number of trades per transaction is just below 10 for the notes and about 4 for the 30-year bond. Roughly two thirds of trades occur in the workup phase.

Panel C shows that transactions without workups tend to be much smaller in size, in terms of both dollar volume and trade count, than those with workups. Moreover, transactions without workups tend to be somewhat smaller than even just the pre-workup portions of transactions with workups. For example, the 2-year note's average transaction size without a workup is about \$12 million, compared with \$16 million pre-workup size and \$42 million total size for transactions with a workup. This is consistent with [Harris \(1997\)](#)'s reasoning



that small traders are usually not concerned with exposure issues, and importantly, the small size is of little interest to other traders. Small trades can also be absorbed more easily by outstanding limit orders. Consequently, small market orders are more likely to be executed without a workup.

Finally, it is useful to compare workups on BrokerTec with those on eSpeed as reported in [Dungey, Henry, and McKenzie \(2013\)](#) for the period January 2006 – October 2006. BrokerTec’s greater market share in terms of total trading volume masks the fact that trading is slightly less frequent on BrokerTec, but that an average transaction has a much greater size.<sup>6</sup> The likelihood of workups is a few percentage points higher on BrokerTec than on eSpeed. However, BrokerTec workups typically discover a slightly smaller proportion of transaction volume. Accordingly, the overall share of workup volume does not differ greatly between the two platforms.

#### 2.4.2 Intradaily Pattern of Workup Usage

Figure 2 plots the probability of workup over the course of a typical trading day, from 18:30 of the previous day to 17:30 of the current day (Eastern Time – ET).<sup>7</sup> The figure shows that workups are most active between 8:30 and 15:00. Outside of New York hours, workup activity is markedly lower, with a mild increase occurring around the start of London trading at 3:00.

One possible interpretation for the lower workup usage in the overnight hours is that it is related to the low overall level of activity during the overnight hours (e.g., [Fleming \(1997\)](#), [Fleming and Mizrach \(2009\)](#)). The workup protocol requires more active monitoring of market activity and exercise of judgment on the part of traders, which are less likely to occur during these hours. In contrast, [Fleming and Mizrach \(2009\)](#) show that the probability

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<sup>6</sup>Our comparison shows that an average transaction in the 2-, 5- or 10-year note is over 40% larger on BrokerTec than on eSpeed, while that in the 30-year bond is about 14% larger.

<sup>7</sup>[Fleming \(1997\)](#) provides a description of the global trading day in U.S. Treasury securities. It starts at 8:30 local time in Tokyo, which is 18:30 EST (or 19:30 EDT) the previous day (Japan has not adopted daylight saving time). Trading then passes on to London at 8:00 local time, i.e., 3:00 ET. New York trading then starts at 7:30 and continues until 17:30. Statistics for the hour from 18:30–19:30 of the previous day are based on the periods over which the U.S. is on standard time.

of hitting/taking an iceberg order during the overnight period is almost double that during New York trading hours (although it is still much smaller than the corresponding probability of workup).

### 2.4.3 Workups and Order Flow

There are further interesting stylized facts relating to trading and workups. Table 2 reports several pairwise correlations of interest. First, the signed order flow imbalance, measured by net order flow as a percentage of total order flow for each day, is only weakly related with workup usage, with the correlation coefficient being under 0.05 for three out of four securities. However, the absolute order imbalance shows a much stronger correlation with the use of workups: except for the 30-year bond, the correlation coefficient is in the negative 0.2 – 0.3 range. That is, we tend to see relatively more workup activities on days when the market is balanced than when it is one-sided, whereas the direction of the imbalance does not matter much. This observation can be interpreted in light of [Sarkar and Schwartz \(2009\)](#)’s notion of market sidedness as an indication of asymmetric information, as informed traders tend to collect on one side of the market. If so, they are more likely to initiate trades to exploit their information advantage quickly, as opposed to trade in workups or post expandable limit orders.

Secondly, workups tend to be used relatively more frequently on more volatile days. This is illustrated by the strong and positive correlation coefficient across all four securities: it is 0.54 for the 2- and 10-year notes, 0.38 for the 5-year note and 0.26 for the 30-year bond. Finally, we also observe positive first order auto-correlation in workup activities, consistent with a liquidity externality effect of workup trades as predicted by [Buti, Rindi, and Werner \(2011a\)](#). Specifically, increased workup activities imply that it is relatively easier to find counter trading interests in workups, thereby increasing the execution probability, and hence attractiveness, of workup orders.

#### 2.4.4 Direction of Workup Volume Expansion

Given the current workup setup on BrokerTec, any trader from either side can join an open workup. Accordingly, volume can be expanded from either the limit order book size, or the aggressive side of the transaction. It is informative to examine the direction of volume expansion in a workup because it is ultimately linked to the degree of pre-trade transparency with respect to liquidity: the level of available liquidity market participants can see before a trade versus what actually shows up in the trade. Moreover, workup volume expansion from the aggressive side suggests the extent to which other traders follow the lead of the initial aggressive trader and provides an indication for the amount of inactive trading interests in the market that gets revealed only when someone else has initiated a trade. Most importantly, the ability to work up volume on either side of a transaction is one of the key features that differentiate BrokerTec’s workup protocol from its voice-assisted precedent.<sup>8</sup>

Figure 3 provides an analysis of the mix of workups with respect to the direction of workup volume expansion. We classify workups into three categories: 1) expanding volume on the aggressive side only, 2) expanding volume on both sides, and 3) expanding volume on the passive side (or both). Specifically, if a transaction’s total volume is not greater than the available depth, all of the workup trades must have come from the aggressive side (category 1). If, instead, a transactions total volume is greater than the available depth, the limit order book must have been expanded during the workup. Whether or not the aggressive side is also expanded can be determined by examining the pre-workup volume. If the pre-workup volume is less than the available depth, it is clear that the workup also expands the aggressive side (category 2). However, if the pre-workup trades completely wipe out the available depth, it is less clear whether the aggressive side is also expanded during the workup, although the

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<sup>8</sup>This is also where BrokerTec’s workup protocol differs from eSpeed’s. As described in one of eSpeed’s patent documents, a market order needs to be sufficiently large to exhaust all display passive orders at the best price in order to trigger a workup, during which the initial parties to the trade are granted the right of first refusal (source: “Systems and Methods for Trading”, patent application publication number US 2004/0210512 A1, dated October 21, 2004). That is, small-sized market orders do not trigger workups and thus the volume expansion on only the aggressive side is not possible under eSpeed’s workup protocol.

passive side is certainly expanded (category 3). Accordingly, the sum of categories 1 and 2 provides a lower bound for the fraction of workups that expand the aggressive side, whereas the sum of categories 2 and 3 shows the percentage of workups that involve expansion on the passive side.

As can be seen from the figure, there is a cross-maturity variation in the direction of workup volume expansion. For the 2-year note, the majority of workups (at least 73%) expands the aggressive side, including the 53% of workups that expand only the aggressive side. Workups that expand the passive side occur 47% of the time. On the other end of the maturity spectrum, for the 30-year bond, workups mostly expand the limit order book (77%). Instances where only the aggressive side is expanded account for only about 22% of workups. The 5- and 10-year notes are in the middle, with nearly 40% of workups expanding the aggressive side only, 23% expanding both sides, and another nearly 40% expanding the passive side or both.

These statistics show that aggressive workups are common for the notes (especially the 2-year) but not for the 30-year bond. In addition, workup trades often come from both sides within a given transaction, accounting for 20% or more of workups in the notes. Taken together, the evidence demonstrates how the current workup protocol on BrokerTec's electronic trading platform differs markedly from the earlier workup protocol described in Boni and Leach (2004).

In order to see if the workup mix documented above is sensitive to different times of day and market conditions, we also analyze the direction of workup volume expansion over different trading hours, on volatile days versus tranquil days, and on days with extreme net order inflow versus net order outflow. In general, the patterns are similar and thus, for brevity, not reported. One finding from our sensitivity analysis that is worth noting is that traders in the notes tend to expand limit orders more often on extremely volatile days, indicating an increase in market opacity. Together with the evidence documented earlier that workups are used more frequently on volatile days, this finding can be reconciled with Boni and Leach

(2004)’s conclusion that limit order expandability is helpful to limit order traders as it helps them reduce pick-off risk and information leakage associated with posting large limit orders during volatile times.

### 3 Informational Value of Workup Trades

We proceed to specify a microstructure model for the dynamics of price and order flow, built upon the general framework described in [Hasbrouck \(2007\)](#). The notable feature of our model is that it accounts explicitly for the segmentation of order flow due to the unique workup feature, as theory suggests that the transparent and dark components of order flow likely have different information values. From this model, we derive a structural VAR representation in (irregular) trade time to be estimated using the data. We then discuss the empirical implementation and findings of the model.

#### 3.1 A Microstructure Model of Price and Trade

Let  $t$  index the  $t^{th}$  market order. We distinguish events occurring during the pre-workup and workup phases of the  $t^{th}$  transaction by the subscripts  $t^-$  and  $t^+$  respectively.  $P_{t-}$  denotes the best bid ask midpoint (logged) observed as of the  $t^{th}$  transaction, and  $m_{t-}$  the unobservable efficient price. Let  $LT_{t-}$  be the signed volume of pre-workup trading (or “lit” trading), and  $(DT_{t+})$  the signed volume of workup trading (or “dark” trading). Both volume variables are positive if the  $t^{th}$  transaction is a buy, and negative if it is a sell.

The basic building blocks of the model are:

$$m_{t-} = m_{t-1} + w_{t-} \quad (1)$$

$$P_{t-} = m_{t-} + cLT_{t-} \quad (2)$$

$$LT_{t-} = v_{1,t-} + \beta_1 v_{1,t-1} \quad (3)$$

$$w_{t-} = u_t^- + \lambda_1 v_{1,t-} + \lambda_2 v_{2,t+1} \quad (4)$$

$$DT_{t+} = v_{2,t+} + \beta_2 v_{2,t+1} + \alpha_1 v_{1,t-} + \alpha_2 u_t^- \quad (5)$$

where the efficient price  $m_{t-}$  is specified to follow a random walk as in equation (1).  $w_{t-}$  is the efficient price increment and the subscript  $t^-$  indicates that the price updating takes place with the execution of the  $t^{th}$  market order, but before the workup begins. The observed price  $P_{t-}$ , as expressed in equation 2, consists of the permanent component  $m_{t-}$  as well as a component reflecting trading frictions ( $cLT_{t-}$ ). Since workup trades are conducted at the price determined in the pre-workup trading round,  $P_{t-}$  depends contemporaneously on the lit trade flow  $LT_{t-}$  but not on the dark trade flow  $DT_{t+}$ .

To allow for the positive auto-correlation of transaction sign as predicted by theory (for example, [Parlour \(1998\)](#)) as well as observed in the data, a MA(1) model is specified for the lit trade as in equation (3), where  $v_{1,t-}$  is a white noise process and captures the pre-workup trade innovation. Likewise, equation (5) for the dark trade flow  $DT_{t+}$  has an MA(1) error structure with the error term  $v_{2,t+}$ . However, it also includes the contemporaneous effect of the innovation in lit trade flow  $v_{1,t-}$  that precedes and initiates the workup process, as well as public information that arrives at the time of the trade  $u_{t-}$ .

Equation (4) models the efficient price increment  $w_{t-}$  as consisting of both a public information component  $u_{t-}$  that is unrelated to trade and a trade-related private information component. The latter component consists of non-public information inferred from the lit trade flow, as well as the lagged dark trade flow. While workup trades have no immediate price implication as they are executed at an established price, traders can observe the workup

trade flows after each transaction and update their belief about the fundamental security value in subsequent transactions. Therefore the dark trading innovation enters the efficient price increment equation with a lag. Finally, the model's innovation terms, namely  $u_{t-}$ ,  $v_{1,t-}$  and  $v_{2,t+}$  are assumed to be uncorrelated.

From this point, we simplify the notation by suppressing the plus and minus superscripts of  $t$ . With this setup, we can derive a VMA(2) for  $Y_t \equiv \begin{bmatrix} LT_t & \Delta P_t & DT_t \end{bmatrix}^T$  with an error vector  $\epsilon_t$ , where  $\epsilon_t$  relates to the model's exogenous variables through the following expression:  $\epsilon_t = B \begin{bmatrix} v_{1,t} & u_t & v_{2,t} \end{bmatrix}^T$ , with:

$$B = \begin{bmatrix} 1 & 0 & 0 \\ \lambda_1 + c & 1 & 0 \\ \alpha_1 & \alpha_2 & 1 \end{bmatrix}. \quad (6)$$

Assuming invertibility condition, a VAR representation (of infinite order) exists for  $Y_t$  with the error vector  $\epsilon_t$  and a covariance matrix  $\Omega \equiv \text{Var}(\epsilon_t)$ . The matrix  $B$  accordingly captures the contemporaneous dynamic structure of the model. It is a lower triangular matrix, reflecting our key assumption with respect to the causal ordering in the model. Specifically, the ordering goes from pre-workup trades to price update and finally to workup trades (which also corresponds to the way we intentionally stack up the vector  $Y_t$ ). Price revision following the pre-workup trade variable reflects the commonly adopted assumption in the literature that traders watch order flow to update their beliefs about the fundamental value of a security. That pre-workup trade variable and price revision precede workup trade variable in the ordering is natural given the way the workup process works: a market order (i.e., non-workup, or originating, trade) must arrive and execute against standing limit orders before the workup process at the established price point can start (hence, a workup trade).

Formulated this way, the model implies that the price revision incorporates two sources of information: 1) public information unrelated to trades ( $u_t$ ), and 2) private information inferred from the contemporaneous trade flow innovation ( $v_{1,t}$ ) and the previous workup trade flow innovation ( $v_{2,t-1}$ ). The role of private and public information in the process of price

formation in the U.S. Treasury bond market has been well studied in the literature (e.g., [Pasquariello and Vega \(2007\)](#)). Our model goes one step further by delineating the sources of private information and quantifying the informational importance of workup trade activities separately from the information content of initiating a market order. For comparison, we also estimate a standard model of the price impact of trades with only the generic transaction volume. We refer to it as the “bivariate” model (as opposed to our “trivariate” model).

### 3.2 Permanent Price Impact of Trades

The VAR representation discussed in the previous section can be fit to the data and the permanent price impact of the respective components of order flow can be evaluated. For empirical implementation, we estimate a structural VAR(5) model. Given the assumed ordering discussed earlier, the structural dynamics (i.e., the matrix  $B$  as well as the structural variance  $\sigma_u^2, \sigma_{v_1}^2$ , and  $\sigma_{v_2}^2$ ) can be fully identified.

The long-run cumulative response of price provides a measure of the permanent price impact which is attributable to information and not to transitory liquidity effects. In other words, it corresponds to the increment in the efficient price  $w_t$ :

$$\mathbb{E}[\Delta P_t + \Delta P_{t+1} + \dots | \epsilon_t] = \Psi_{\infty, P} \epsilon_t \quad (7)$$

We approximate  $\Psi_{\infty, P}$  by computing the cumulative impulse response function (IRF) out to a sufficiently long horizon over which the price response has stabilized and any transitory effects have washed out. As is standard in the literature, we compute the IRF for price from the estimated VAR model by forecasting the system recursively forward to the chosen horizon, assuming that the system is initially at rest, i.e., all variables are set to 0 except for the shocked variable. Inspection of the path of the estimated IRFs indicates that a horizon of 50 transactions provides a reasonable approximation of the permanent price impact  $\Psi_{\infty, P}$ . The price impact is measured with units in hundredths of a percent of par value (basis points),



which is equivalent to in cents per \$100 par value. The model is estimated separately for each day in our sample.

Figure 4 plots the average cumulative change in price up to 25 transactions following an initial \$1 billion shock in trade volume initiated from the buy side. The figure shows clearly that the transparent part of order flow has a greater price impact than the dark part for most securities. The only exception is in the 2-year note, where the impact of the pre-workup and workup trade flows is comparable. The figure also shows that the cumulative price response has largely settled by the fifth transaction.

The estimated permanent price impact per \$1 billion shock is reported in Table 3. The table shows the mean and the 95% range of the time series of the daily price impact estimates separately for pre-workup trade flow (under “Lit Trades” column) and workup trade flow (under “Dark Trades” column). The mean impact is monotonically increasing in maturity, and this pattern applies to both the pre-workup and workup trade flow. At the shorter end, the 2-year note price increases by merely 3.7 bps if the trading volume during the pre-workup phase increases by \$1 billion. In sharp contrast, the same shock, if it occurs in the 30-year bond, induces a permanent increase of nearly 400 bps, about a hundred times larger. With respect to workup trade flow, the differential in the price impact between the two maturity ends is not as extreme: 51 bps for the 30-year maturity versus 3 bps for the 2-year one. In between, the 5- and 10-year notes exhibit a more moderate difference: the price impact of the latter is slightly more than twice that of the former. The ranges of price impact estimates for lit and dark trade flow also generally respect the ordering by maturity just discussed, except for the 30-year bond where a much wider range is documented.

Finally, it is useful to look at the variation over time of the price impact to gain an understanding of how market liquidity has evolved. Figure 5 plots the 20-day moving average of price impact over the sample period. Considering first the price impact of initiating a market order, one can see a significant increase during the crisis period (from August 2007 to June 2009), with the sharpest increases (to about four-eight times larger than the pre-crisis

level) occurring in late 2008. This is consistent with the patterns of market depth and bid–ask spreads, other measures of market liquidity, shown in [Engle, Fleming, Ghysels, and Nguyen \(2012\)](#), in suggesting that the market was markedly less liquid during the crisis.

The price impact of workup trades also varies significantly over time, albeit less so than the price impact of pre–workup trades, with a mild increase during the crisis period. There is thus roughly a doubling of price impact from the pre-crisis level to the peak of the crisis for the 5–, 10–, and 30–year securities, versus a four– to six–fold increase for the pre-workup trades. For the 2-year note, there is roughly a quadrupling of price impact at the peak of the crisis for the workup trades, versus a roughly eight-fold increase for the pre-workup trades. The differential response during the crisis means that the 2-year note’s price impact estimates for pre–workup and workup trades, which are similar for the pre-crisis period, separate out during the crisis. Taken together, the evidence indicates that initiating a trade produces a greater impact than waiting to trade the same quantity during a workup, and more so during times of crisis.

### 3.3 Information Content of Workup Trades

To evaluate the informational value of workup trades, we follow the information share framework as introduced in [Hasbrouck \(1991\)](#) and applied widely in subsequent studies of price discovery. Conceptually, the information share of a variable measures the extent to which its variation contributes to the variance of the efficient price update  $w_t$ . From equation (7), this variance can be approximated by:

$$\tilde{\sigma}_w^2 = \Psi_{h,P} \Omega \Psi_{h,P}^T \quad (8)$$

Given the structure of the system, it is easy to show that the right–hand side of equation (8) is a linear combination of  $\sigma_u^2$ ,  $\sigma_{v_1}^2$ , and  $\sigma_{v_2}^2$ . Each of these terms can then be expressed as a percentage of  $\sigma_w^2$  – such percentage is referred to as the “Hasbrouck information share” of the

relevant variable. Specifically, the percentage attributable to  $\sigma_u^2$  indicates the extent to which public information drives the variation in the efficient price updates, whereas those attributable to  $\sigma_{v_1}^2$ , and  $\sigma_{v_2}^2$  quantify the contribution of non-public information revealed through the trade flows during the pre-workup and workup phases respectively. The information share statistics thus allow us to disentangle the information structure and determine the degree of private information being conveyed in workups in comparison to that conveyed through the normal/visible trade flows.

The information share estimates are reported in Table 4. For trade-related information share, we observe that the informativeness of the lit trade flow is quite consistent across all four securities, ranging on average between 15% and 19%. This part of order flow explains about 30% or more of the total variation in the efficient price innovations in 2.5% of the sample (except for the 5-year note with the 95% upper bound of roughly 26%).

In contrast, there is a much wider range for the informational value of workup trades across maturities. On the one hand, the dark trade flow of the 2-year note contributes about 17% – slightly higher than the contribution of the lit trade flow. On the other hand, there is almost no private information revealed by the workup trade flow for the 30-year bond (1%). Even the 95% upper bound for the bond is only about 5%. In between, the 5- and 10-year notes are quite similar in terms of workup trade informativeness, with an average contribution of 7 and 8% respectively, and a corresponding 95% upper bound of 18% and 21%.

The table also shows that public information is still the main driver of the variation in the efficient price innovations. For the 5- and 10-year notes, the average contribution of public information to the price discovery process is between 73–77%, with a 95% range of roughly 60–90%. The 30-year bond has a slightly higher public information share, with a mean of 82% and a 95% range between 69% and 94%. The 2-year note shows a slightly lower public information share, averaging 67% and ranging between 42% and 88%. That is, trade flow is most informative at the short maturity end and least informative at the long

maturity end. Moreover, the breakdown between lit and dark trades shows that this overall differential between public information and trade-related information is explained mainly by the differential in the informativeness of workups.

### 3.4 Information Structure on Special Days

We now analyze the information structure on days of special interest in particular. We specifically look at days with important announcements, days when the market is highly volatile, and days when the market experiences extreme buying pressure – an indicator of a possible flight-to-safety. Table 5 documents this analysis. Under each security, there are three columns: Lit Trades, Dark Trades and Public Information. Different from Table 4 where we report the raw information shares of lit and dark trades, in this table, the respective shares have been standardized by the total trade-related information share, i.e., these two columns add up to 100%. This makes it easier to see the relative informational importance of lit versus dark trade flow. The private versus public information split can be gauged by examining the public information share reported in the third column for each security.

#### 3.4.1 Announcement Days

In Table 5, Panel A, we compare non-announcement days to days with announcements of: 1) FOMC rate decisions, 2) important macroeconomic releases, and 3) auction results.<sup>9</sup> These announcements have been shown to be important to Treasury price formation (see [Fleming and Remolona \(1997\)](#), [Balduzzi, Elton, and Green \(2001\)](#), [Green \(2004\)](#), [Pasquariello and Vega \(2007\)](#) and references therein). For each of these announcement types, we compare the relative informativeness of the lit and dark trade flows on announcement days with that estimated on days when none of the three announcement types listed above occurs.

Interestingly, there is no major change in the private information structure on announcement days, as compared to non-announcement days. That is, the mix of information content

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<sup>9</sup>See Appendix A for the list of announcements considered.

of lit and dark trade flow remains quite similar across different announcement types (including no announcement). However, the trade flow collectively has relatively less information value on FOMC and macroeconomic announcement days. This result is intuitive, because there is a greater amount of public information arriving on these announcement days which can move prices without requiring trades, as discussed and documented in [Fleming and Remolona \(1999\)](#) and others.

### 3.4.2 Volatile Days

Table 5, Panel B shows a comparison of the information structure on highly volatile days against days with low volatility (based on the 95th and 5th percentiles of the volatility distribution). We first focus on the private information mix. Evidently and consistently across all four securities, the pre-workup trade flow – the lit part – is relatively more informative on high volatility days. It is helpful to tie this result to an earlier stylized fact that workups are used more on volatile days, and, particularly for the notes, more often expand the quoted depth. We interpret these results collectively as indicating that: 1) information is short-lived in volatile times, necessitating fast execution and 2) the increased incidence of quoted depth expansion reflects how liquidity providers (not necessarily informed) use the workup option to guard against adverse execution of their orders.

It is also interesting to see that public information takes on a greater role in the price discovery when the market is highly volatile, as compared to when the market is tranquil. That trades are less informational when price is highly volatile is to be expected, since the variance of the efficient price updates is a linear combination of the variances of return and two order flow variables. When price fluctuates greatly, this variability dominates the variance of the efficient price updates, leaving a lesser role for trade-related information in the price formation process. An intuitive way to think about this result is that noisier public information makes it harder for market participants to interpret trade flow patterns and discern value-relevant information.

### 3.4.3 Days with Extreme Net Order Flow

In Table 5, Panel C, we compare the information structure on days with high net inflows and high net outflows (based on the 95th and 5th percentiles of the distribution of net order flow). Net order flow, if strongly positive, signals a possible flight into Treasury securities (see [Beber, Brandt, and Kavajecz \(2009\)](#)), whereas strongly negative net order flow hints at a flight out of Treasury securities. The results show that the 2- and 10-year notes do not exhibit a statistically significant change in the information structure between flights into and out of Treasuries. In contrast, the long order flow of the 5- and 30-year securities becomes relatively more informative on days with high flows into the market, compared to flows out of the market. However, the shift is fairly small in magnitude. Furthermore, most securities show a similar public information share between high inflow and high outflow days. Overall, the nature of the flows in the market does not seem to alter substantially the information structure and workup characteristics.

## 3.5 Comparison with Standard Model of Price Impact of Trades

Our analysis in the previous section illustrates that delineating the trade flow into the pre-workup and workup components permits a more complete understanding of how the different layers of the trading process convey non-public information and affect price dynamics. One of the key findings is that trade flow is not homogeneous. A \$1 million trade initiated in the pre-workup stage generally results in a greater price impact and carries more information than when the same trade occurs in the workup stage.

As a result, if we model only the trade volume variable without considering its respective components, we may underestimate the price impact of a market order, since the lower impact of the workup component pulls down the estimate for the whole transaction size. In addition, omitting the possible endogenous interaction of workup and pre-workup activity might underestimate the overall informativeness of order flow. To formally see this, we estimate a bivariate VAR(5) of trade flow and return, and compute the permanent price impact as well

as the information share of transaction volume. The comparison to the trivariate results is provided in Table 6.

The table illustrates for the 5-, 10- and 30-year securities that the price impact of a lumped-together (or “generic”) trade estimated from the bivariate model is much smaller than the price impact of a market order of the same size estimated from the trivariate model (about half the magnitude). At the same time, the price impact of a generic trade is higher than the price impact of trades occurring during workups.

For the 2-year note, the estimated price impact of a generic trade is not only lower than the estimated price impact of a market order, but also lower than the price impact of workup trades. As discussed earlier, workup activity in the 2-year note is generally as informative as pre-workup trading activity. Failure of the bivariate model to capture the endogenous dynamics between workups and trade initiation featured in our trivariate model results in a lower price impact estimate than that of workups in the 2-year note.

Additionally and relatedly, the bivariate model attributes less information value to order flow. Our tests of the hypothesis that the information share of trades in the model of segmented order flow is not higher than that implied by the bivariate model are rejected for three of the four securities considered. This is because the bivariate model does not capture and attribute adequately the different contributions and variations in the respective components of the overall order flow. More importantly, as discussed above, the dynamic interaction between pre-workup and workup activity in explaining variation in the price process is absent in the bivariate model, implying a lower information role of order flow than is the case when this dynamic interaction is taken into account.

Economically, it is important to recognize that the workup option is an integral part of the trading process in the Treasury interdealer market. It is undoubtedly factored into the trading decisions of dealers, since they can choose to trade immediately by submitting a market order, or wait to trade in a workup. Factors such as liquidity need, degree of impatience and/or possession of short- versus long-lived information might contribute to

the segmentation of order flow, as dealers balance faster execution with higher price impact. Treating this market as one where such a workup option is not available and trade flow is homogeneous may give rise to a less than accurate/realistic characterization of the trading process and how trading affects price dynamics.

## 4 Determinants of Workup Trades

As the previous section shows, trading activity that takes place during the workup stage has a non-trivial role in the price discovery process. Additionally, workups take place in more than half of the transactions and account for a large share of volume transacted in this market. Collectively, these findings provide a motivation for our subsequent analysis aimed at exploring in greater depth what determines the use of the workup option and the extent of volume transacted during this phase. Being able to predict the likelihood and extent of a workup upon the arrival of the next market order, based on the prevailing market conditions, can be valuable to market participants in making trading decisions.

### 4.1 Hypothesis Development

Choosing whether to hide one's trading intention from the market and subsequently realize it during a workup involves costs. The most natural cost is the risk of non-execution, since counter trading interests may not exist in a workup. For those traders with high disutility for non-execution, such as those with very short-lived private information, the workup protocol may be less valuable.

On the other hand, the obvious benefit of the workup protocol is that traders have more flexibility with what to do with their trading intention, including not doing anything at all if the market moves unfavorably. This provides an important advantage over iceberg orders, since the hidden part of an iceberg order may get executed adversely before the trader has a chance to modify or cancel. Furthermore, the ability to expand volume during workups



can be valuable to those traders with a large trading interest. By submitting an initial small sized order, those traders can avoid causing adverse price impact that could have resulted had they submitted the full-sized large order altogether.

The use of workups thereby reflects a trade-off among non-execution risk, increased control over one's trading activities, and the ability to avoid adverse price impact. These risks and benefits, however, are arguably varying with market conditions. Thus, we seek to understand the market conditions under which workups are more useful for traders, and, conditional on the exercise of the workup option, how the extent of volume expansion can be predicted. For this purpose, we rely on the literature on dark pool trading and hidden liquidity for guidance in developing hypotheses and formulating our empirical model.

[Buti, Rindi, and Werner \(2011a\)](#)'s model of dark pool trading strategies in limit order markets makes several predictions. First, dark pool trading is more likely if the current inside order book depth on the same side is high or the spread is low. Both indicate a greater degree of competition for liquidity provision. Greater inside depth reduces the execution probability for the marginal limit order. Accordingly, we expect that, all else being equal, for each transaction, higher prevailing inside depth on the same side is associated with higher probability of workup and higher workup volume.

Likewise, a tighter spread (especially when the spread is already at the minimum of 1 tick) makes it harder to post limit orders inside the spread, while simultaneously reducing the cost to trade at the workup price (i.e., the forgone spread). Thus, the choice of immediate execution, despite it being worse than a limit order price, becomes more attractive. Only one trader can submit a market order at a time, but other traders with trading interest on the same side and at the same price can join the workup initiated by the market order. Thus, it is expected that the narrower the prevailing spread, the more likely the workup and the higher the volume transacted during such workup.

Another issue for market participants to consider is the potential price impact of their trade. [Buti, Rindi, and Werner](#) argue that, if there is lower depth on the opposite side to

absorb the incoming order, initiating a large market order can generate more adverse price pressure. As a result, a trader with a large trading intention may be more inclined to send a smaller market order and hope to expand the volume in the workup stage. At the same time, however, lower depth on the opposite side may be a sign that trading interest on that side is lacking and can potentially reduce the execution probability of trades in a workup. Which effect prevails is open to empirical investigation.

The fourth factor we consider is price volatility, which has been empirically shown in [Boni and Leach \(2004\)](#) to affect the use of workups, as traders resort to this mechanism to mitigate the risk of stale limit orders. When the market is volatile, this risk increases and hence motivates a greater reliance on workups as the protocol allows traders greater control over when and how much to trade. Furthermore, since the workup protocol can be likened to a crossing network, we can also borrow theoretical insights from that literature. [Ye \(2012\)](#) suggests a linkage between security value uncertainty and the choice of trading in the crossing network as opposed to the transparent exchange. Specifically, uncertainty increases both the price impact of trades on the exchange and the non-execution probability in the crossing network, but the net effect is that the crossing network is comparatively more beneficial for the informed traders. As a result, [Ye](#) predicts that crossing network usage should increase in value uncertainty.

Nevertheless, the empirical literature provides mixed evidence. [Ready \(2012\)](#) finds evidence generally consistent with this prediction in a cross section of the 500 largest NASDAQ stocks from 2005 to 2007. On the contrary, [Buti, Rindi, and Werner \(2011b\)](#) report an opposite result that dark pool activity is significantly higher on days with low intraday volatility and low absolute returns, using data for a large cross section of US stocks in 2009. Against this backdrop, we seek to test [Ye \(2012\)](#) model prediction in the Treasury market setup where the workup protocol serves as a de facto crossing network. We hypothesize that higher price volatility is associated with higher workup usage and greater volume discovered when workups are used.

Fifth, the volume transacted during the pre-workup stage may have a direct bearing on whether there is further trading interest going into the workup. For example, there may be inactive traders in the market who only take action based on the actions of other, as explained in [Harris \(1997\)](#). Another possibility is that large initial volume is perceived by the market as associated with large liquidity demand. This may induce the expansion of the quoted depth during the workup beyond the level observed just before the trade. Empirically, Boni and Leach (2004) find that transaction size is a determinant of workups. We thus expect that higher pre-workup trading volume predicts greater likelihood of a subsequent workup and a larger quantity of worked-up volume.

Lastly, the revelation of hidden depth during the initial execution phase is hypothesized to predict a greater likelihood of workups and larger volume expansion. This is because market participants can observe if some hidden depth in the book has been exposed, which indicates a greater availability of liquidity than initially thought and raises the likelihood of successful execution for workup orders.

## 4.2 Empirical Results

For workup usage, we model both the probability of workup (i.e., whether or not a transaction has a workup), as well as the magnitude of the worked up volume. We specify a logistic regression model for the probability of workup, and a Tobit model for the volume expansion during a workup, treating those transactions with no workup as being censored at the 0 bound. To control for the possible different workup patterns outside New York trading hours, we include two dummies for Tokyo and London trading hours respectively. Our specification for both models includes the following explanatory variables:

- *DepthSame*: prevailing inside depth on the same side of the transaction (logged).
- *DepthOpp*: prevailing inside depth on the opposite side of the transaction (logged).
- *PretradeSpr*: prevailing relative spread in basis points  $\left(10,000 \frac{P_A - P_B}{(P_A + P_B)/2}\right)$ .

- *MoSize*: pre-workup volume of the transaction (i.e., the volume transacted before the workup start) (logged).
- *HdRevealed*: whether trading activities during the pre-workup stage have revealed any iceberg orders.
- *AveDurLast5*: average transaction duration (in seconds) in the last five minute interval (logged).
- *Vola5Min*: volatility as measured by the high low range of the logged midquote over the last five minute interval, capturing the level of volatility immediately before the transaction.
- *PctWkup5Min*: percentage of transactions with a workup in the last five minute interval, to control for the possible liquidity externality of workup activities as predicted by Buti, Rindi, and Werner (2011a)'s model.
- *PctWkupV5Min*: percentage of volume expanded during workups (conditional on workup usage) in the last five minute interval. This is another control for the possible liquidity externality.
- *Tokyo trading hour dummy*: equal 1 if the transaction starts during the period from 18:30 EST (or 19:30 EDT) the previous day up to but not including 3:00 ET.
- *London trading hour dummy*: equal 1 if the transaction starts during the period from 3:00 ET up to but not including 7:30 ET.

The model estimates are presented in Table 7. Given the large number of observations, most of the coefficient estimates are significant at the 5% level. Only those coefficients that are not significant are marked with an asterisk. As expected, the prevailing depth on the same side is positively related with both the probability of workup and the magnitude of workup volume. This supports the argument that a higher level of depth, indicative of possibly a

longer time to execution for the marginal limit order, might encourage traders with trading interest on the same side to opt for the immediate execution opportunity offered by the workup. This finding is enhanced by the negative relationship between prevailing spread and the likelihood of workup. A tighter spread makes the immediate execution option less costly, in addition to the effect that a quote-improving limit order may not be possible.

Our results also show that depth on the opposite side generally has a positive coefficient, providing support for the argument that this greater availability of depth increases the probability of workup trades and the magnitude of workup volume. This is particularly so when the extra trading demand in a workup originates from the aggressive side. The only exception is the 2-year note, for which we observe a negative correlation between depth on the opposite side and the likelihood of a workup. It is worth recalling that the transaction size in the 2-year note is often much larger than that for other securities. Accordingly, the adverse price impact associated with the lack of opposite standing depth may encourage greater usage of workups to fill a large market order without walking deeper into the book.

That workups are more likely for larger transactions is generally supported by the estimated logit model, as shown by the positive coefficients for pre-workup volume (except for the 30-year bond). This result illustrates a possible explanation for the observation that transactions in this market rarely walk deeper into the book. This is because workups provide the opportunity to invite further counter-party interest at the same price point to the transaction, so the initiating trader does not have to submit a multiple price order in the first place. And, as reasoned by [Harris \(1997\)](#), a large volume transacted during the pre-workup phase can ignite interest from otherwise inactive traders. Interestingly, once a workup is taking place, the additional volume transacted may increase or decrease with the pre-workup volume depending on the security. For example, it is positive for the 2- and 30-year securities but negative for the 5- and 10-year notes.

Another aspect of pre-workup trading – the revelation of hidden depth – can also predict higher workup usage and volume expansion. The revelation informs market participants that

there is a hidden liquidity pool in addition to the initially observed depth and that workup trades have a greater chance of being filled/absorbed.

Beside the prevailing state of the order book at the time of the transaction, other variables capturing general market conditions around the time of a transaction are also important in explaining the use and volume of workups. Volatility, measured over the 5-minute time window leading to each transaction, is positively related with workup activities. This finding is consistent with [Boni and Leach \(2004\)](#)'s evidence that workups are more likely in volatile times when traders have a need to mitigate adverse execution risk, which increases in price volatility. Additionally, the speed of trading in the market significantly increases the likelihood of a workup, as well as the magnitude of worked-up volume. In light of [Easley and O'Hara \(1992\)](#) and [Dufour and Engle \(2000\)](#), high trading intensity is likely reflective of information arrival, and thus, inactive trading interests can be activated and revealed in a workup following the lead of market order traders. Furthermore, the positive coefficients for the prevailing level of workup activity support [Buti, Rindi, and Werner \(2011a\)](#)'s argument that dark pool liquidity begets dark pool liquidity, as a higher level of workup activity signals an increased chance of finding counter-party trading interest and successful execution of workup orders.

Finally, the probability of workups and extent of worked up volume are both significantly lower outside New York trading hours, even after having controlled for the level of trading activity through the previously discussed covariates. This seems to be consistent with the hypothesis that workups are used less in the overnight hours when there are fewer traders in the market.

## 5 Conclusion

This paper studies the workup protocol, a unique and frequently used trading feature in the U.S. Treasury securities market. Given its importance in discovering a large portion of market liquidity, we examine its role in the price formation process, and distinguish it

from the information value of non-workup trades that initiate workups. Being more opaque, the workup trade flow generally contains less information than its transparent counterpart, but its role is not trivial. For the 2-year note in particular, it is roughly as informative as the lit trade flow. The only exception is the 30-year bond, for which there is little private information revealed in workups. For this bond, workups mostly expand the limit order book, whereas aggressive side workups are more common for the notes.

Furthermore, we find that workups tend to be used more around volatile times, and that the incidence of workups expanding the pre-trade limit order book increases on volatile days for all three notes, suggesting that the workup protocol is helpful to limit order traders in managing their trading interest. Additionally, workups are also more likely when the market is more liquid (e.g., greater market depth and tighter bid-ask spreads) or trading more actively. Interestingly, lit order flow becomes more informationally relevant on highly volatile days, supporting the belief that traders with better information are more likely to initiate trades and exploit their information before adverse price movements can render the information less valuable. Taken together, the evidence seems to suggest that workups are used more as a channel for liquidity providers to guard against adverse price movements, than as a channel to hide private information.

Our findings provide important implications for research into the price discovery of U.S. Treasury securities. Consistent with theory, we document that the different layers of order flow have different information content. Intuitively, given the option of trading in a workup, a trader who chooses to initiate a trade (as opposed to wait for a workup) conveys a stronger signal to the market than otherwise would be the case in a hypothetical market setup where such workup option does not exist. Therefore, the act of initiating a trade should contribute more to information discovery than the act of trading in a workup. We show that, without considering this segmentation, the price impact so estimated can underestimate the impact of initiating a trade and the share of non-public information flow.

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**Table 1:** Summary Statistics of Trading and Workup Activities

	2-Year	5-Year	10-Year	30-Year
PANEL A: DAY-LEVEL STATISTICS				
Volume (\$B)	33.5	34.0	29.3	4.7
<i>Pre-workup %</i>	51.8	43.6	45.5	57.3
<i>Workup %</i>	48.2	56.4	54.5	42.7
Number of Transactions	1,224	2,679	2,642	1,464
<i>% with Workup</i>	49.0	56.2	55.2	39.1
<i>% with Iceberg Order Match</i>	4.2	4.3	4.4	3.9
<i>% Executed at Multiple Prices</i>	0.0	0.2	0.2	0.5
PANEL B: TRANSACTION-LEVEL STATISTICS (WITH WORKUP)				
Transaction Size (\$M)	41.8	18.6	16.4	5.4
<i>Pre-workup</i>	15.6	6.0	5.5	1.9
<i>Workup</i>	26.2	12.7	10.9	3.5
Number of Trades	9.9	8.7	8.6	3.9
<i>Pre-workup</i>	3.2	2.9	3.0	1.4
<i>Workup</i>	6.7	5.8	5.6	2.5
PANEL C: TRANSACTION-LEVEL STATISTICS (WITHOUT WORKUP)				
Transaction Size (\$M)	11.9	4.6	4.2	1.7
Number of Trades	2.4	2.1	2.2	1.3
PANEL D: SAMPLE SIZE				
Number of Transactions	1,836,812	4,017,905	3,946,216	2,197,471
Number of Trading Days	1,501	1,501	1,494	1,501

This table provides key summary statistics of trading activity in the on-the-run 2-, 5-, 10-, and 30-year Treasury securities on the BrokerTec platform. The sample period is 2006–2011. A transaction refers to a complete sequence of order executions that starts with the arrival of a market order and ends when the workup initiated by the original market order completes. A trade refers to a single paired order matching. There is no data available for the 10-year note on seven days during the sample period (August 3–7, 10–11, 2009).

**Table 2:** Correlations of Workup and Order Flow Variables

	2-Year	5-Year	10-Year	30-Year
Daily Signed Order Imbalance & Workup Usage	0.048	0.169	0.043	0.043
Daily Absolute Order Imbalance & Workup Usage	-0.297	-0.266	-0.206	-0.081
Daily Volatility & Workup Usage	0.541	0.380	0.540	0.256
Workup Autocorrelation	0.110	0.084	0.089	0.063
Workup Volume Autocorrelation	0.098	0.120	0.136	0.114

This table shows correlations of workup and trading variables for the on-the-run 2-, 5-, 10-, and 30-year Treasury securities on the BrokerTec platform. The sample period is 2006–2011. A transaction refers to a complete sequence of order executions that starts with the arrival of a market order and ends when the workup initiated by the original market order completes. Daily signed order imbalance is buy volume minus sell volume, standardized by the day’s total trading volume. Daily absolute order imbalance is the absolute order imbalance standardized by the day’s total trading volume. Daily volatility is the average five-minute realized volatility of the bid–ask midpoint (logged) for each day. Workup usage is the percentage of transactions with workups for each day. The workup and workup volume autocorrelation coefficients are computed based on transaction-level data.

**Table 3:** Permanent Price Impact of Segmented Order Flow

		Lit Trades	Dark Trades
2-Year	Mean	3.70	3.19
	95% Range Lower Bound	0.76	0.88
	95% Range Upper Bound	13.59	8.57
5-Year	Mean	21.88	7.54
	95% Range Lower Bound	5.23	2.59
	95% Range Upper Bound	59.42	15.44
10-Year	Mean	48.16	18.04
	95% Range Lower Bound	11.02	6.24
	95% Range Upper Bound	129.36	34.00
30-Year	Mean	397.97	50.60
	95% Range Lower Bound	113.59	-61.24
	95% Range Upper Bound	938.46	203.19

This table reports the permanent price impact (in basis points per \$1 billion buyer-initiated volume) of pre-workup trades (“Lit Trades”) versus workup trades (“Dark Trades”). The estimates derive from a VAR(5) model of pre-workup trade flow, return and workup trade flow. Estimation is based on BrokerTec data for the on-the-run 2-, 5-, 10- and 30-year Treasury securities over the period 2006–2011. Observations outside the [7:00–17:30] time window are excluded. The model is estimated separately for each day. The mean and 95% range are computed from the time series of daily price impact estimates.

**Table 4:** Share of Trade and Non-Trade Related Information

		Trade Related Information		Public
		Lit Trades	Dark Trades	Information
2-Year	Mean	15.23	17.48	67.28
	95% Range Lower Bound	3.52	3.01	41.72
	95% Range Upper Bound	30.67	38.67	87.73
5-Year	Mean	16.09	6.72	77.19
	95% Range Lower Bound	6.07	0.54	63.19
	95% Range Upper Bound	26.35	17.82	91.08
10-Year	Mean	18.52	8.21	73.28
	95% Range Lower Bound	7.83	0.67	59.11
	95% Range Upper Bound	30.10	21.19	86.53
30-Year	Mean	16.66	1.05	82.29
	95% Range Lower Bound	5.66	0.00	68.69
	95% Range Upper Bound	29.95	5.13	93.73

This table reports the information share (%) of pre-workup trades (“Lit Trades”), workup trades (“Dark Trades”), and non-trade-related information (“Public Information”). The estimates derive from a VAR(5) model of pre-workup trade flow, return and workup trade flow. Estimation is based on BrokerTec data for the on-the-run 2-, 5-, 10- and 30-year Treasury securities over the period 2006–2011. Observations outside the [7:00–17:30] time window are excluded. The model is estimated separately for each day. The mean and 95% range are computed from the time series of daily information share estimates.

**Table 5:** Information Structure on Days with Announcements and Extreme Market Movements

	2-Year			5-Year			10-Year			30-Year		
	Lit Trades	Dark Trades	Public Info	Lit Trades	Dark Trades	Public Info	Lit Trades	Dark Trades	Public Info	Lit Trades	Dark Trades	Public Info
PANEL A: Announcement Versus Non-Announcement Days												
FOMC Announcements	47.66	52.34	72.58*	72.51	27.49	84.19*	71.27	28.73	78.94*	94.38	5.62	86.34*
Macro. Announcements	47.82	52.18	67.93*	72.22	27.78	78.30*	70.84	29.16	74.15*	93.60	6.40	83.05*
Auction Days	47.03	52.97	66.89	70.79	29.21	77.76*	69.95	30.05	73.01	95.38	4.62	82.36
Non-Announcement Days	49.30	50.70	66.18	71.56	28.44	75.29	69.72	30.28	71.83	93.84	6.16	81.02
PANEL B: Days with Extreme Volatility												
High Volatility. Days	62.30*	37.70*	78.94*	83.51*	16.49*	84.28*	86.18*	13.82*	78.10*	95.70*	4.30*	83.66
Low Volatility Days	48.47	51.53	67.48	72.66	27.34	77.40	71.25	28.75	73.56	93.97	6.03	82.45
PANEL C: Days with Extreme Order Imbalances												
High Inflow Days	50.11	49.89	66.15	76.64*	23.36*	76.53	68.72	31.28	73.03	95.69*	4.31*	84.01*
High Outflow Days	48.30	51.70	67.21	72.09	27.91	77.14	70.67	29.33	73.28	93.69	6.31	82.29

This table reports the relative informativeness of pre-workup (“Lit Trades”) versus workup order flow (“Dark Trades”) and the share of public information (“Public Info”) on: A) days with announcements versus non-announcement days; B) high volatility days versus low volatility days; and C) high inflow days versus high outflow days. The thresholds for high and low volatility, and similarly for high inflow and high outflow, are the 95th and 5th percentiles of the distributions for volatility and net order flow (Buy Volume minus Sell Volume) respectively. The relative informativeness of each component of the order flow is measured by its information share as a percentage of the total trade-related information share. The public information share is 100% minus the total trade-related information share. The information shares are computed from a VAR(5) model of pre-workup trade flow, return and workup trade flow. Estimation is based on BrokerTec data for on-the-run 2-, 5-, 10- and 30-year Treasury securities over the period 2006–2011. Observations outside the [7:00–17:30] time window are excluded. An asterisk (\*) indicates significantly different informativeness at 5% level.

**Table 6:** Informational Content of Segmented versus Generic Order Flow

	2-Year	5-Year	10-Year	30-Year
<i>Price Impact of \$1 Billion <b>Pre-Workup</b> Volume:</i>				
Model with Segmented Trade Flow	3.70	21.88	48.16	397.97
Model with Generic Trade Flow	2.74	11.34	25.94	181.00
p-value of paired sample t-test (right tail)	<0.001	<0.001	<0.001	<0.001
<i>Price Impact of \$1 Billion <b>Workup</b> Volume:</i>				
Model with Segmented Trade Flow	3.19	7.54	18.04	50.60
Model with Generic Trade Flow	2.74	11.34	25.94	181.00
p-value of paired sample t-test (left tail)	1.000	<0.001	<0.001	<0.001
<i>Information Share of Trades:</i>				
Model with Segmented Trade Flow**	32.72%	22.81%	26.72%	17.71%
Model with Generic Trade Flow	26.64%	22.76%	26.39%	14.45%
p-value of paired sample t-test (right tail)	<0.001	0.201	<0.001	<0.001

This table compares the price impact and informational content of order flow estimated by our trivariate VAR model, that considers separately the pre-workup and workup order flow, with those estimated by a standard bivariate VAR model, that considers the generic order flow without segmentation. The data is from BrokerTec and covers 2006–2011. \*\* This is the combined information share of pre-workup and workup trades.

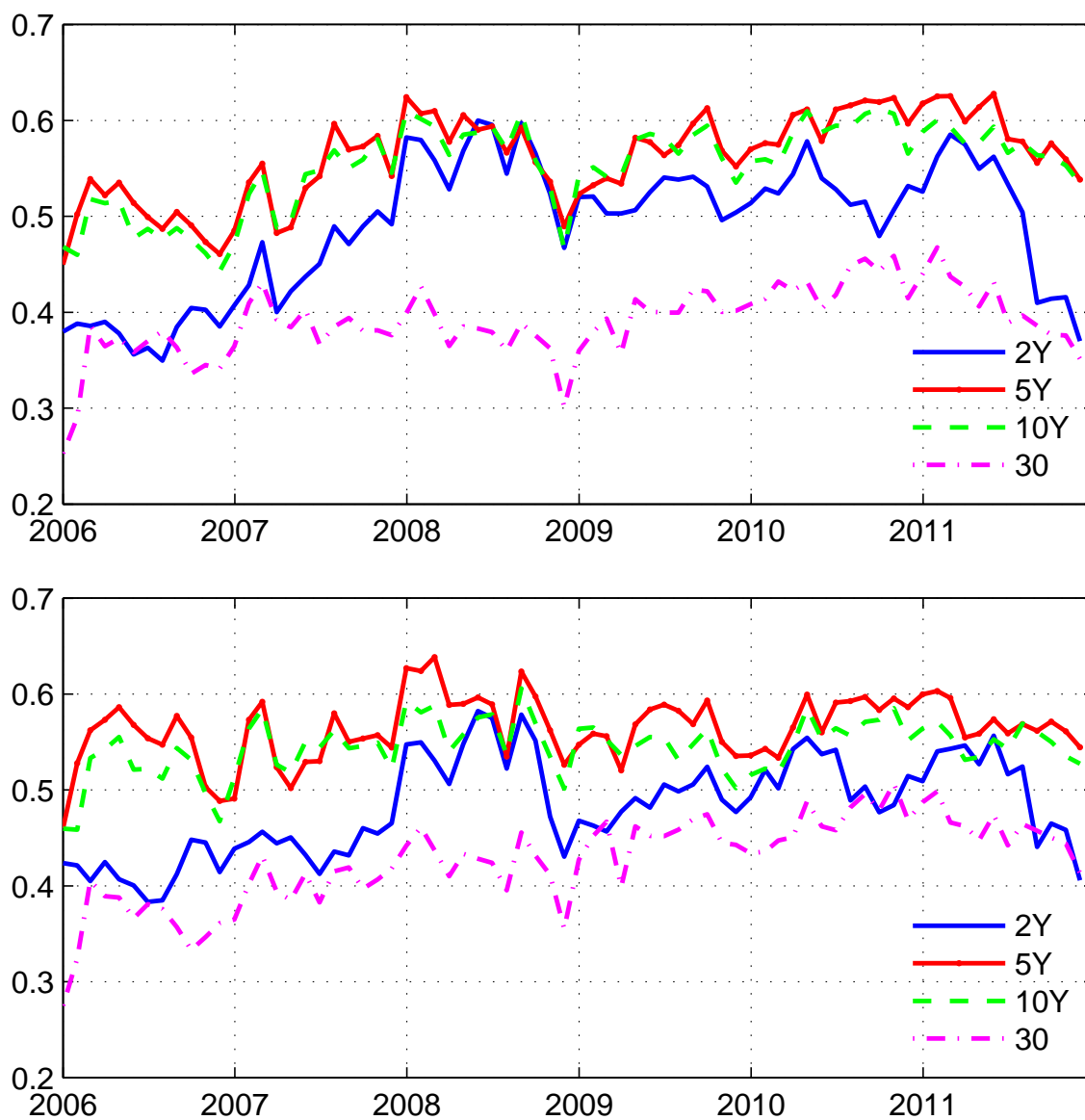


**Table 7:** Determinants of Workups

	2-Year		5-Year		10-Year		30-Year	
	Probability	Quantity	Probability	Quantity	Probability	Quantity	Probability	Quantity
Intercept	-0.037	0.650	-0.031	0.556	0.104	0.556	-0.413	0.670
Pretrade Depth – Same Side	0.131	0.175	0.145	0.164	0.147	0.167	0.049	0.065
Pretrade Depth – Opposite Side	-0.101	0.277	0.081	0.357	0.046	0.365	0.522	0.219
Pretrade Spread	-0.217	-0.067	-0.240	0.008	-0.172	-0.008	-0.009	0.010
Pre-workup Volume (logged)	0.095	0.079	0.081	-0.009	0.087	-0.035	-0.193	0.019
Hidden Depth Revealed	0.156	0.303	0.419	0.414	0.338	0.374	0.992	0.323
Ave Duration Last5Mins (logged)	-0.174	-0.082	-0.264	-0.094	-0.265	-0.109	-0.207	-0.067
Volatility Last5Mins	0.084	0.066	0.042	0.024	0.030	0.013	0.007	0.002
Workup Probability Last5Mins	0.496	0.052	0.641	0.161	0.586	0.162	0.406	0.163
Workup Volume Share Last5Mins	0.176	0.023	0.066	0.016	0.115	0.007 *	0.115	-0.013
Tokyo Trading Hour Dummy	-0.369	-0.131	-0.185	-0.225	-0.308	-0.193	-0.502	-0.119
London Trading Hour Dummy	-0.278	-0.205	-0.134	-0.221	-0.168	-0.237	-0.191	-0.103
Max-rescaled Rsquared	0.063		0.076		0.083		0.079	

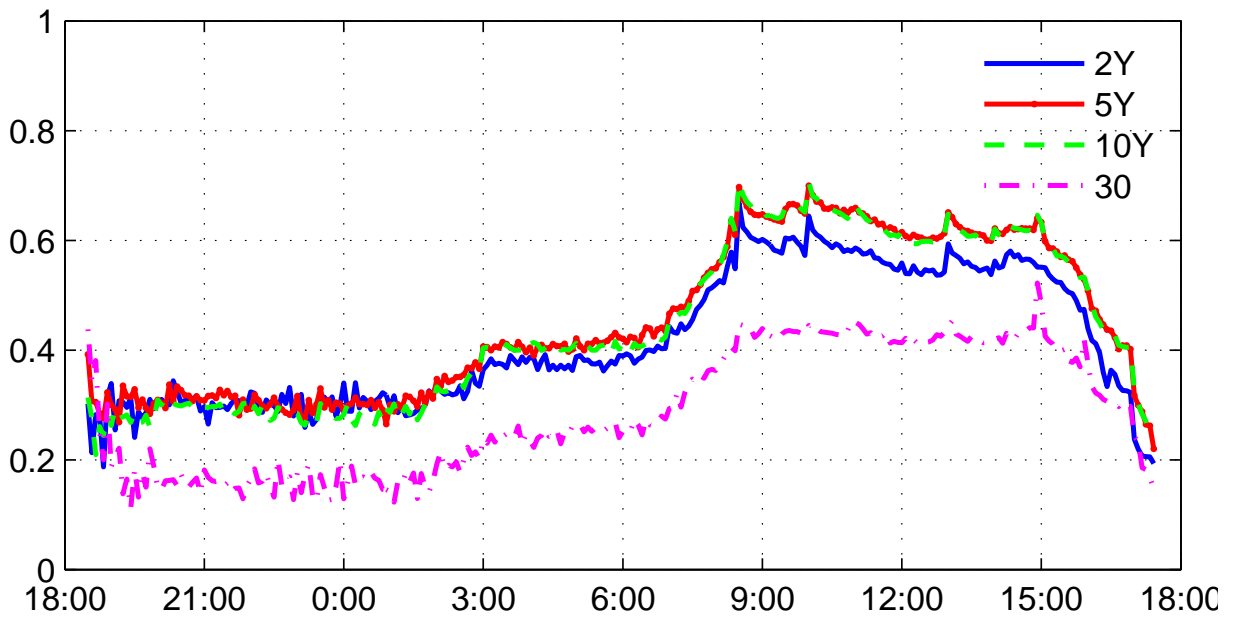
This table reports results of a logistic regression for whether or not a transaction has workup (under columns titled “Probability”), and a Tobit model for the dollar volume transacted during the workup phase (under columns titled “Quantity”). The models are estimated using BrokerTec data for on-the-run 2-, 5-, 10-, and 30-year Treasury securities over the period 2006–2011. Tokyo trading hour dummy is equal 1 for the period from 18:30 EST (or 19:30 EDT) the previous day to 3:00 ET. London trading hour dummy is equal 1 for the period from 3:00 ET to 7:30 ET. Note: an asterisk (\*) indicates *insignificance* at 5% level.

**Figure 1: Workup Activity over Time**



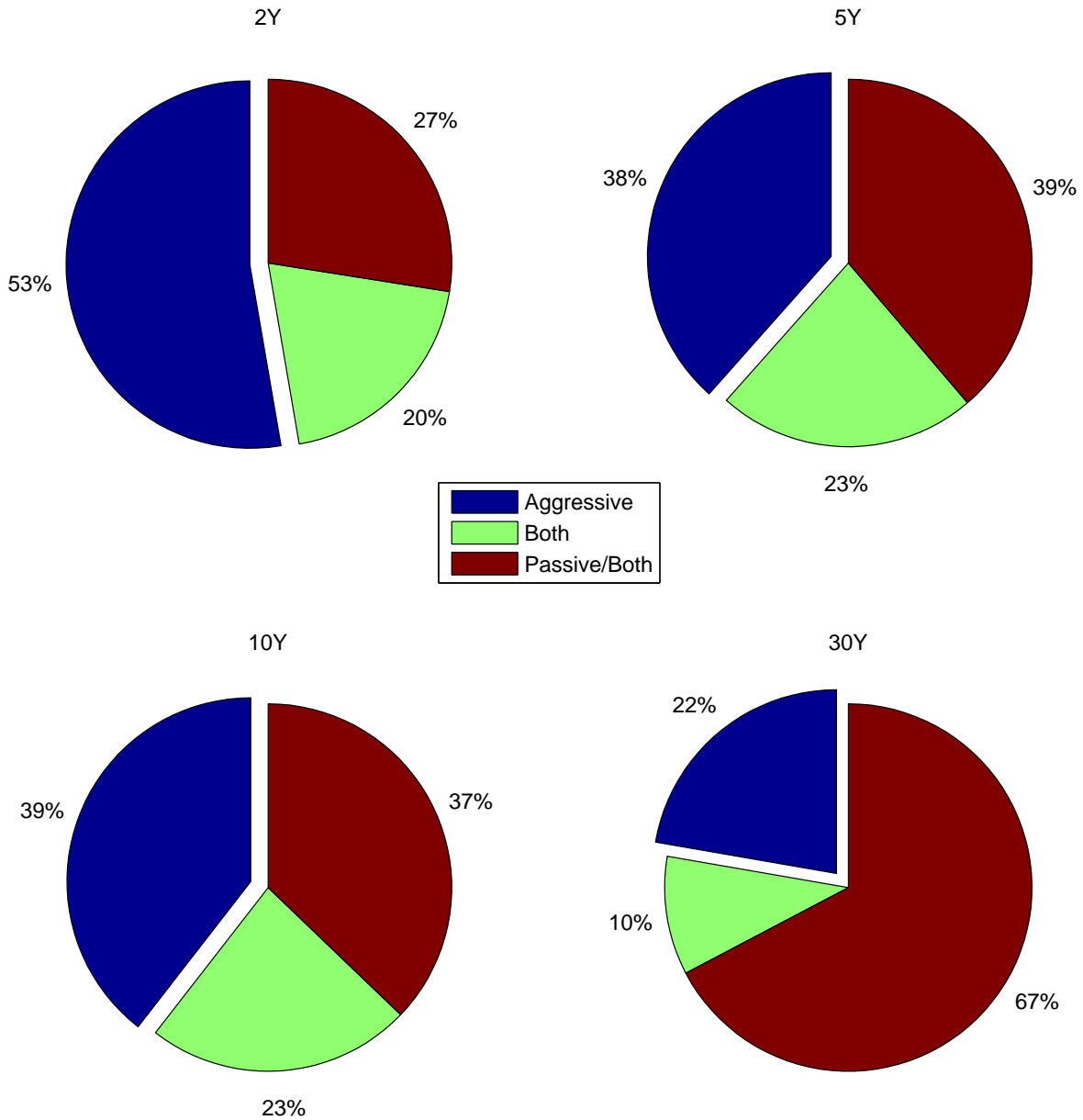
This figure shows the monthly average share of transactions with workups (upper plot) and monthly average share of volume transacted in workups (lower plot). It is based on BrokerTec trade data over the period 2006–2011.

**Figure 2:** Intraday Pattern of Workup Probability



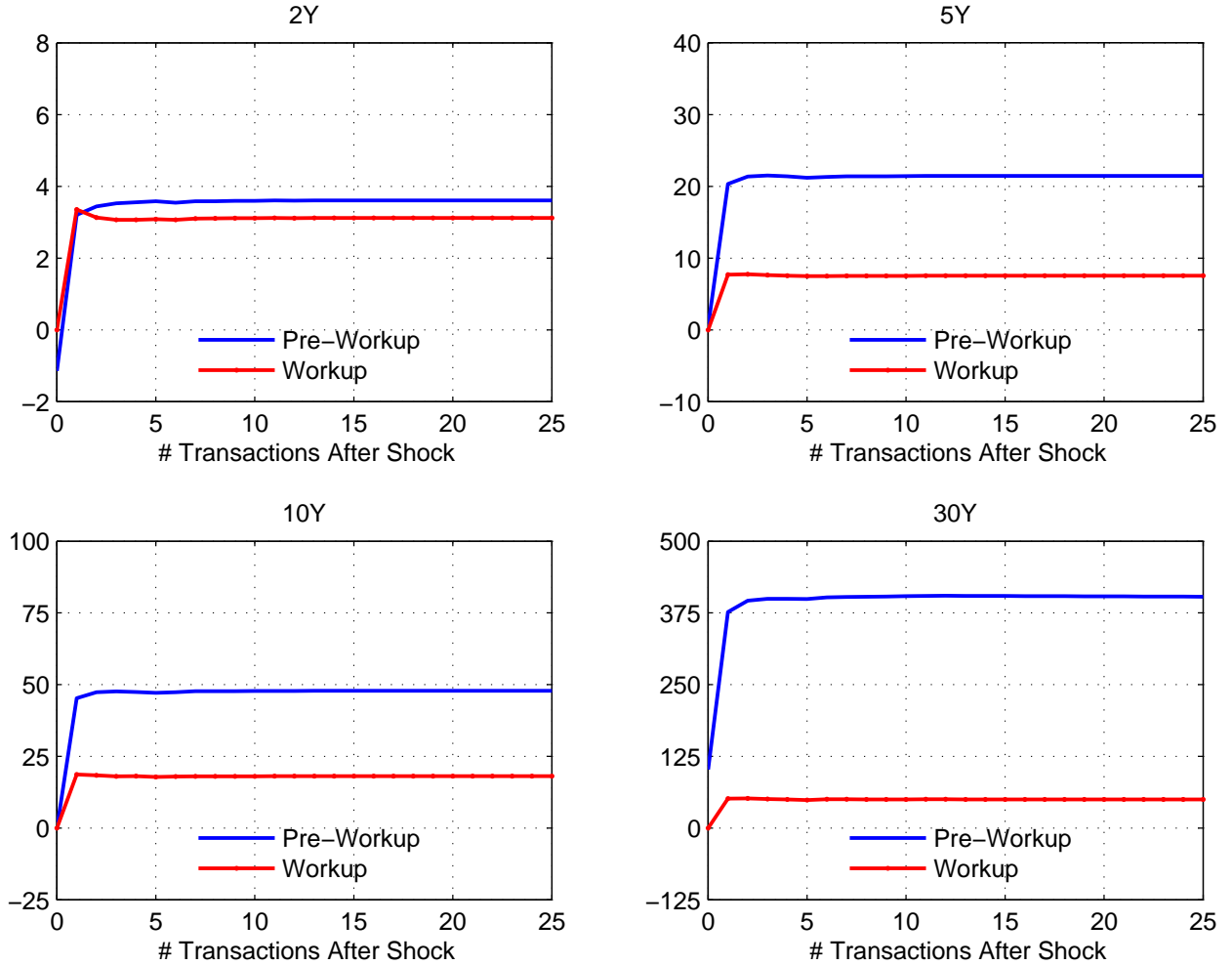
This figure shows the pattern of workup usage over the global trading day (Eastern Time). The plot starts at 18:30 of the previous day and ends at 17:30 of the current day. It is based on BrokerTec trade data over the period 2006–2011.

**Figure 3:** Which Side Do Workups Expand?



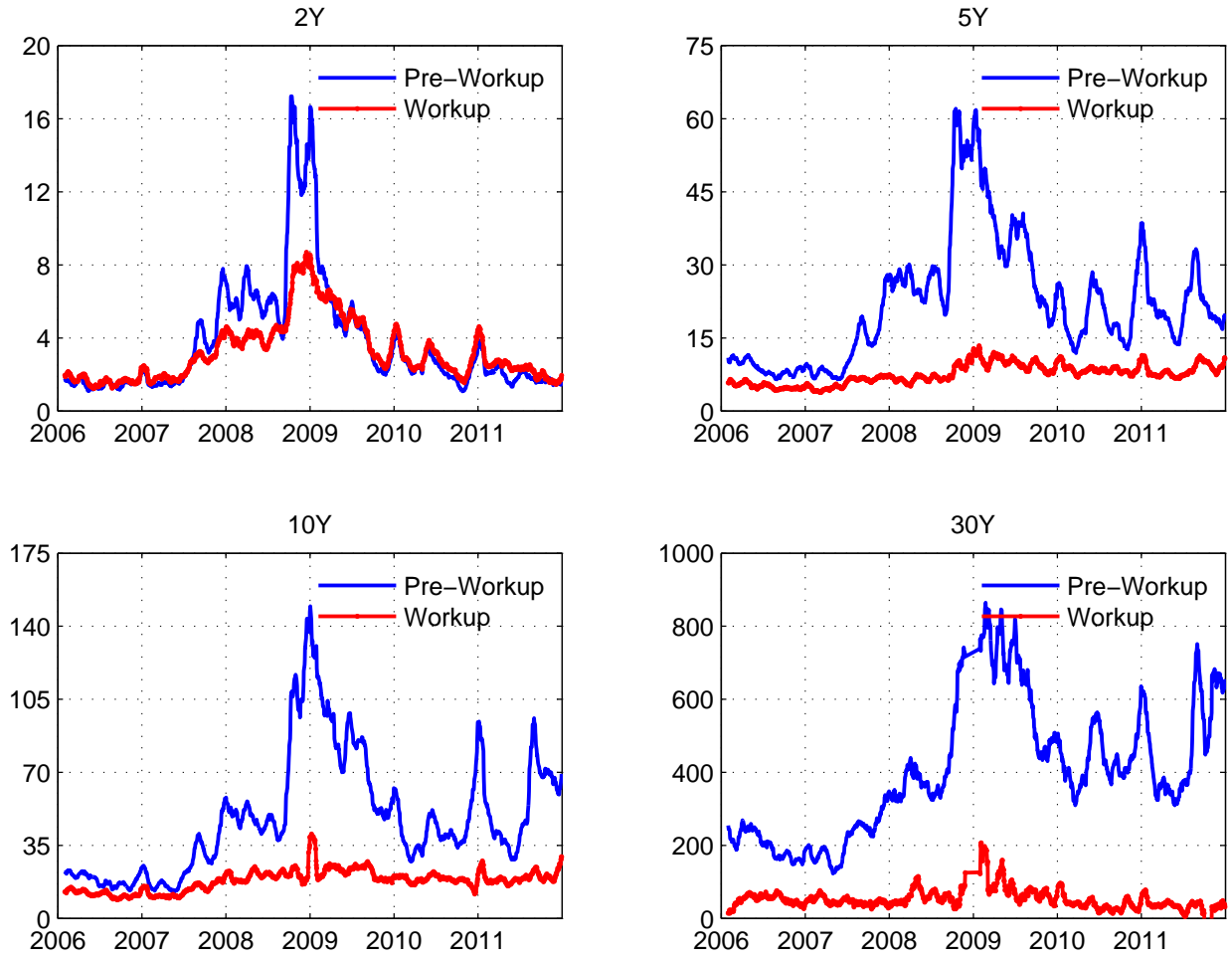
This figure shows the percentages of workups that expand volume on: 1) the aggressive side only, 2) both sides, and 3) passive side. A workup expands only the aggressive side if the total transaction volume (pre-workup and workup volume combined) is not greater than the depth posted in the limit order book immediately before the transaction. A workup expands both sides if the pre-workup volume is less than the posted depth, but the total transaction volume exceeds the posted depth. A workup expands the passive side if the pre-workup trades exhaust the posted depth. This expansion of the passive side includes instances where the aggressive side is also expanded during the workup. The percentages are calculated for the on-the-run 2-, 5-, 10-, and 30-year Treasury securities on the BrokerTec platform. The sample period is 2006–2011.

**Figure 4:** Cumulative Impulse Response of Price to Trade



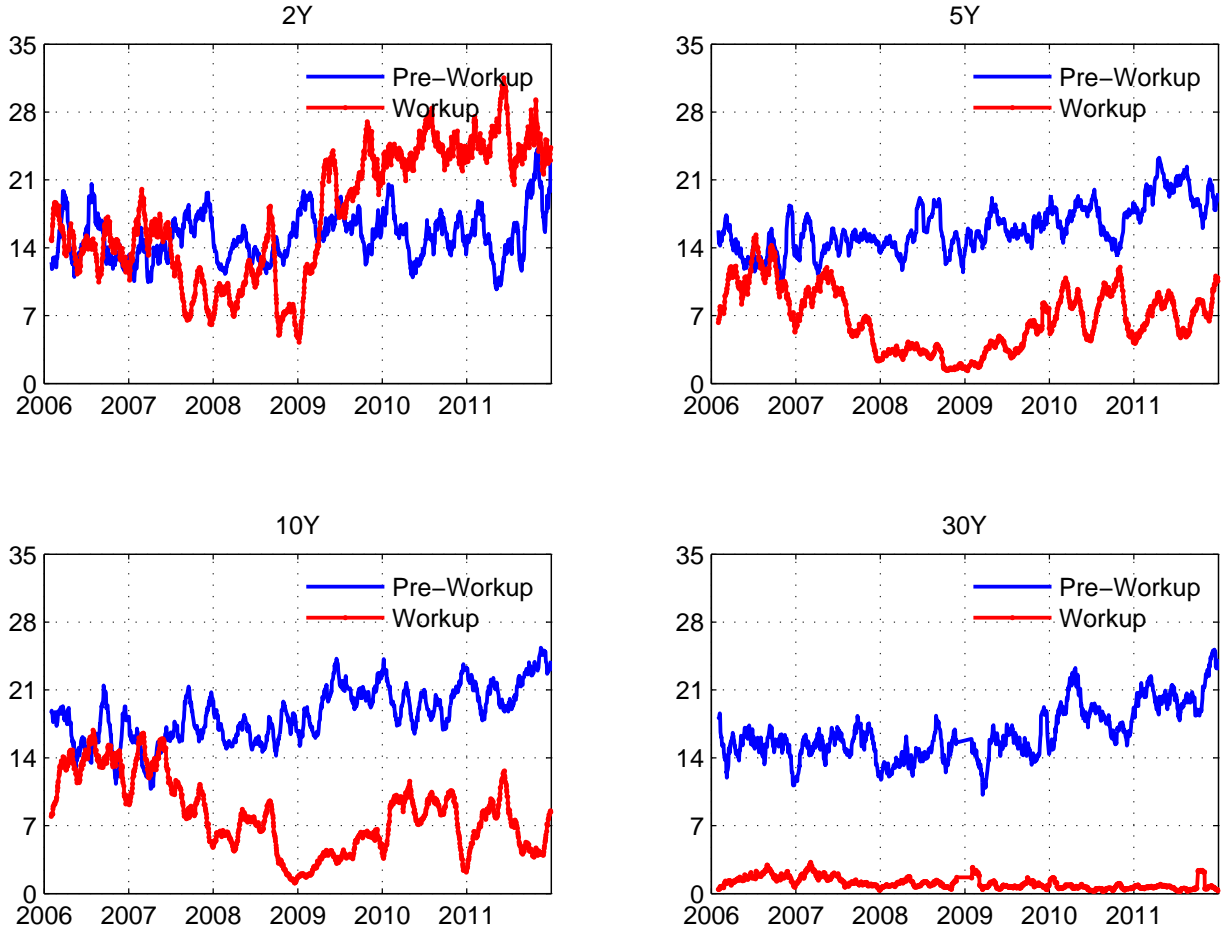
This figure plots the cumulative midpoint return (in basis points) in response to a \$1 billion shock to pre-workup and workup trading volume respectively, based on a VAR(5) model of return and segmented order flow. Estimation is based on BrokerTec data for the on-the-run 2-, 5-, 10- and 30-year Treasury securities over the period 2006–2011. Observations outside the [7:00–17:30] time window are excluded from model estimation.

**Figure 5:** Permanent Price Impact of Trade



This figure plots the 20-day moving average of the price impact of \$1 billion buyer-initiated volume transacted during pre-workup versus workup phases, based on a VAR(5) model of return and trade flows. Estimation is based on BrokerTec data for the on-the-run 2-, 5-, 10- and 30-year Treasury securities over the period 2006–2011. Observations outside the [7:00–17:30] time window are excluded from model estimation.

**Figure 6:** Information Share of Pre-Workup and Workup Order Flow



This figure plots the 20-day moving average of the information share of pre-workup versus workup order flow, using [Hasbrouck \(1991\)](#)'s information share approach. The information share measures are computed from a VAR(5) model of return and trade flows. Estimation is based on BrokerTec data for the on-the-run 2-, 5-, 10- and 30-year Treasury securities over the period 2006–2011. Observations outside the [7:00–17:30] time window are excluded from model estimation.

## **A Economic Announcements**

We consider three categories of news that are relevant for the Treasury market: 1) macroeconomic announcements, 2) monetary policy announcements (i.e., FOMC rate decision announcements), and 3) Treasury auction results.

### **A.1 Macroeconomic Announcements**

These are major economic announcements classified as "Market Moving" indicators by Bloomberg: 1) Employment Report, 2) Consumer Price Index, 3) Durable Goods Orders, 4) GDP, 5) Housing Starts, 6) Initial Jobless Claims, 7) Personal Income and Outlays, 8) Producer Price Index, 9) Retail Sales, 10) Trade Balance, 11) Industrial Production, 12) Existing Home Sales, 13) ISM Manufacturing, 14) New Home Sales, and 15) Philadelphia Fed Survey.

### **A.2 Monetary Policy Announcements**

Included in our analysis are FOMC rate decision announcements. Such announcements typically occur after regularly scheduled FOMC meetings, of which there are eight per year. In addition, there were two rate changes announced after unscheduled meetings during our sample period, on January 22, 2008 and October 8, 2008.

### **A.3 Treasury Auction Result Announcements**

Auction results are announced shortly after the auction close on auction dates for the relevant security. The 2- and 5-year notes are newly issued every month. The 10-year note is newly issued every quarter, with reopenings in the following month and – since November 2008 – two months. Starting in May 2009, the 30-year bond is also on a quarterly issuance cycle with two reopenings. For the 2006–2008 period, the 30-year bond was newly issued once every year with irregular reopenings.