# Internet Appendix (Not For Publication) to "Government Intervention and Strategic Trading in the U.S. Treasury Market"

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In this Internet Appendix to Pasquariello, Roush, and Vega (2018), we discuss various extensions to our model and the robustness of its implications (in Section 1), as well as assess both the robustness of the accompanying supportive evidence in Table 3 and its conformity to alternative interpretations (in Section 2 and attached additional tables).

# 1 Model Extensions and Robustness

The discussion in Section II.B of Pasquariello et al. (2018) makes it clear that our model's main predictions about the effects of government intervention on market liquidity stem from the conditional uncertainty among market participants (i.e., given their information endowments) about the central bank's non-public, uninformative policy target $p_T$. With knowledge of the central bank's loss function (equation (4)), rational market-makers (MMs) would account for the portion of its trading activity driven by a *public*, uninformative $p_T$ (i.e., $\sigma_T^2 = 0$) in the aggregate order flow $\omega_1$, thus making such pursuit ineffective (Vitale (1999)). Credible, *fully* informative announcements about asset fundamentals ($v$), like those by the Federal Open Market Committee (FOMC) since 1994, would be fully and immediately incorporated into market participants' expectations and equilibrium prices ($p_1 = v$), thus thwarting speculation and making the market infinitely deep for liquidity trading ($\lambda_{\text{CB}} = 0$).[1]

Our model's implications for market liquidity in Conclusion 1 are also qualitatively unaffected (yet its analysis is more analytically involved) by making the central bank's non-public policy target $p_T$ at least *partially* correlated with the traded asset's payoff $v$ (as in Bhattacharya and Weller (1997), Pasquariello (2018)). For instance, assume that $p_T$ is some unspecified function of the central bank's private, informative signal $S_{\text{CB}}$ such that $\text{cov}[p_T, S_{\text{CB}}] = \sigma_{\text{CB}}^2$ and $\text{cov}[S_v(m), p_T] = \text{cov}(v, p_T) = \sigma_v^2$. Intuitively, $\text{cov}(v, p_T) > 0$ has three additional effects on MMs' perceived adverse selection risk, relative to when $\text{cov}(v, p_T) = 0$. First, a partially informative policy target $p_T$ is less urgent for the central bank to pursue given extant informed speculation, hence making government intervention less aggressive; this may increase MMs' perceived adverse selection risk. Second, MMs can learn about a partially informative policy target $p_T$ from fundamental information in the aggregate order flow $\omega_1$; in addition, so-motivated government intervention makes $\omega_1$ itself more informative about asset fundamentals $v$; both may decrease the MMs' perceived adverse selection risk. Third, the central bank's pursuit of a par-

[1] See also Pasquariello and Vega (2007), (2009). For studies of the economics of disclosing public information as an information choice problem, see, e.g., Stein (1989), Veldkamp (2011), Bond and Goldstein (2015), and Pasquariello and Wang (2018).

tially informative policy target makes speculators' private information about $v$ less valuable and their trading activity more cautious; this may increase the MMs' perceived adverse selection risk. It can be shown that, in equilibrium, the first and third effects of $\mathrm{cov}(v, p_T) > 0$ prevail upon the second such that the presence of a central bank continues to improve market liquidity, albeit less so than when its policy target is uninformative — even ceteris paribus for unconditional policy uncertainty $\sigma_T^2$.

As noted in Section II.B of Pasquariello et al. (2018), our insights from the numerical analysis of Proposition 2 are generally robust to parameter selection. A noteworthy yet nonrobust exception to Conclusion 1 may arise in our model when the central bank is virtually (or, at the limit, altogether) *uninterested* in its policy motives (low (or zero) $\gamma$), so that its intervention activity $x_{\mathrm{CB}}$ closely (or fully) resembles informed speculation and the resulting equilibrium is similar to (or the same as) the one of Proposition 1. Ceteris paribus, such an intervention may worsen equilibrium market liquidity ($\Delta\lambda > 0$), yet only in the presence of few or very heterogeneously informed speculators (low $M$ or $\rho$). In those extreme and arguably less plausible circumstances (especially relative to the Federal Reserve Bank of New York's (FRBNY) explicitly stated POMO policy), the resulting more intense competition in speculation is more than offset by more strategic, informed trading activity in the aggregate order flow, ultimately increasing adverse selection risk for the MMs.[2]

Lastly, we noted earlier that the central bank's loss function of equation (4) is based on extant theoretical literature on government intervention (e.g., see Bhattacharya and Weller (1997, eq. (1))). Equation (4) is both tractable and consistent with this literature's intuitive notion that governments may balance expected trading losses against expected policy success when setting their intervention strategies. However, the above discussion also implies that our model's main predictions are likely to be robust to any alternative loss function yielding nontrivial optimal intervention (i.e., $|x_{\mathrm{CB}}| < \infty$) driven (at least partly) by the pursuit of (at least partly uninformative) policy targets.

[2] Accordingly, in the basic model of Section II.A of Pasquariello et al. (2018), the finite difference $\lambda\,(\text{at } M+1) - \lambda\,(\text{at } M) = \frac{\sigma_v\left\{[2+(M-1)\rho]\sqrt{(M+1)\rho}-(2+M\rho)\sqrt{M\rho}\right\}}{\sigma_z(2+M\rho)[2+(M-1)\rho]} > 0$ in the equilibrium of Proposition 1 (equation (3)) only in the small region of $\{M, \rho\}$ where $M$ is low (and $\rho$ is not too high) or $\rho$ is low (since $\frac{\partial\lambda}{\partial M} = -\frac{\sigma_v\sqrt{\rho}[(M+1)\rho-2]}{2\sigma_z\sqrt{M}[2+(M-1)\rho]^2} > 0$ when $M < \frac{2-\rho}{\rho}$, $\rho \in (0,1)$, and $M$ is a discrete number); see also the discussion in Pasquariello and Vega (2007), (2009), (2015), and Pasquariello (2018).

# 2 POMOs and Market Liquidity: Robustness

The evidence in Table 3 suggests that Treasury market liquidity improves on POMO days, consistent with the main prediction of our model. In this section, we assess the robustness of this evidence and its conformity to alternative interpretations.

## 2.1 Sample-Specific Issues

As discussed in Section III.A.1 of Pasquariello et al. (2018), bid-ask spreads are much wider (and more volatile) during the earlier portion of our sample, 2001–2004. That period encompasses both significant economic and financial uncertainty — e.g., the bursting of the Internet bubble, the events of 9/11, the short NBER recession in the Fall of 2001, and the accompanying changes in the Federal Reserve's monetary policy (see Figure 3) — as well as the gradual migration of most trading in on-the-run Treasury securities from the voice-brokered GovPX platform to two electronic platforms — BrokerTec and eSpeed. In addition, Table 2 and Figure 3 also indicate that permanent open market operations (POMOs) occur nearly twice more often over 2001–2004 than over 2005–2007.

As noted earlier, our regression specifications include time-trend and calendar variables to control for deterministic changes in bid-ask spreads over the sample period 2001–2007. We further assess the effect of the changing characteristics of our sample in two ways. First, we estimate $\overline{\Delta S_{i,t}^{B}}$, $\gamma_{i,\text{CB}}$, and $\alpha_{i,\text{CB}}$ separately within either the earlier subsample 2001–2004 (in Panel A of Table IA-1) or the later one 2005–2007 (in Panel B of Table IA-1). According to our model (Conclusion 1), government intervention improves market liquidity by a greater extent when liquidity is already low (and adverse selection risk high), e.g., because of high fundamental uncertainty (as in 2001–2004). Consistently, Table IA-1 indicates that while bid-ask spreads for Treasury securities tend to be lower on POMO days in both subperiods, estimates for $\overline{\Delta S_{i,t}^{B}} < 0$, $\gamma_{i,\text{CB}} < 0$, and $\alpha_{i,\text{CB}} < 0$ are larger and more often significant in the earlier (low-liquidity, high-POMO frequency) subperiod than in the later (high-liquidity, low-POMO frequency) one. Thus, this evidence may provide further support for our model. We explore more directly the role of fundamental uncertainty for our inference in Section IV.C.2 of Pasquariello et al. (2018).

Second, we extend our analysis to all available GovPX data within our sample period. This data includes price midquotes and bid-ask spreads for 2-year, 3-year, 5-year, and 10-year notes between 2001 and 2004. Voice-brokered trading in on-the-run securities virtually ceases afterward. We then estimate $\overline{\Delta S_{i,t}^{B}}$, $\gamma_{i,\text{CB}}$, and $\alpha_{i,\text{CB}}$ within this dataset. These estimates (in Panel C of Table IA-1) are similar in sign, magnitude, and significance to those from our BrokerTec sample. This suggests that our inference cannot be attributed to the use of BrokerTec data.

## 2.2 The 2008 Financial Crisis

We also extend our analysis to the recent period of financial turmoil in the aftermath of the collapse of Bear Stearns and Lehman Brothers in 2008. Our model is not designed to capture both the determinants of Treasury market liquidity and the unique nature of government intervention in those special circumstances. With this caveat in mind, such times of distress may be accompanied by high fundamental uncertainty (high $\sigma_v^2$; see also Graphs C and D of Figure 4) and information heterogeneity (low $\rho$; see also Graphs A and B of Figure 4), as well as rapidly deteriorating market depth (high $\lambda$; see also Figure 2). In those circumstances, government intervention may be aimed at improving marketwide liquidity provision in the secondary Treasury market (e.g., by targeting not only price levels $[p_T]$ but also market depth itself $[\lambda]$) and/or account for bond-specific illiquidity in its implementation (given its relatively high frequency and large magnitude; see, e.g., Song and Zhu (2018)). It is also plausible that in those circumstances, the central bank may set potentially informative policy objectives (i.e., $\text{cov}(v, p_T) > 0$), reduce uncertainty about them (e.g., lower $\sigma_T^2$; see also Graph E of Figure 4), and/or pursue them more aggressively (e.g., higher $\gamma$ in equation (4)). As noted in Section 1, all of these forces may have large yet conflicting effects on equilibrium market liquidity in the presence of government intervention.

In light of this discussion, we consider the net impact of these forces on our inference by augmenting our sample to include any POMO executed by the FRBNY over the immediate crisis period between Jan. 1, 2008 and Dec. 31, 2009. Importantly, this period encompasses the Federal Reserve's pursuit of significant "quantitative easing" via POMOs. At the Mar. 2009 Federal Open Market Committee (FOMC) meeting, and contrary to its established modus operandi, the Federal Reserve announced its intention to execute extraordinary large POMOs (and some details about their characteristics) in advance, when directing the Desk to purchase up to $300 billion of long-term Treasury securities over the subsequent six months (e.g., see Figure 3). The Desk executed this policy program — known as Large-Scale Asset Purchases (LSAP) — over several trading days between Mar. 25 and Oct. 29, 2009. In those cases, the Desk first announced the broad maturity segment it targeted and the days in which it was planning to trade about two weeks in advance (D'Amico and King (2013)).[3] Summary statistics on these POMOs are in Panel D of Table 2. There are 75 POMO days over the immediate crisis period

[3] Subsequent LSAP programs over 2010–2012 (known as LSAP-2, Maturity Extension Program (MEP), and LSAP-3) followed similar procedures (Kitsul (2013)).

2008–2009. Interestingly, in a few of them (18, all in 2008) the Desk sold Treasury securities. As noted above, average number of securities traded on POMO days and daily par amounts accepted at POMO auctions during 2008–2009 are several times larger than during the basic sample period 2001–2007. According to Panel D of Table 1 and Figure 2, bid-ask spreads on Treasury securities also widen considerably during 2008–2009, e.g., by an average of 27% relative to their pre-crisis means over 2005–2007 (in Panel C of Table 1).

Table IA-2 reports estimates for $\overline{\Delta S_{i,t}^B}$, $\gamma_{i,\text{CB}}$, and $\alpha_{i,\text{CB}}$ over the extended sample 2001–2009 (Panel A), as well as over the sub-period 2008–2009 for POMO purchases (Panel B) and POMO sales (Panel C). According to Table IA-2, i) our inference is qualitatively unaffected by the inclusion of the immediate crisis period; and ii) *both* POMO purchases and sales during the crisis period are accompanied on average by tighter bid-ask spreads — as predicted by our model — although the estimated improvement in liquidity is statistically significant almost exclusively for POMO purchases (perhaps due to the small number of POMO sales in the merged BrokerTec/POMO sample). Consistently, Kitsul (2013) finds that (various measures of) Treasury market liquidity improved in correspondence with all LSAPs (and LSAP-related announcements) by the Desk between Mar. 2009 and Oct. 2012. We conclude that the estimated liquidity externalities of POMOs during the recent financial crisis are consistent with our model's main prediction, notwithstanding the crisis' likely effects on both liquidity provision and government intervention policy in the Treasury market. We consider alternative interpretations of these findings in Section 2.4.

## 2.3 Alternative Specifications

The empirical evidence in Table 3 is based on comparing daily averages of intraday bid-ask price spreads for on-the-run Treasury securities on days when POMOs occurred ($S_{i,t}$) to those averages on the past 22 days when no POMOs occurred ($S_{i,t}^B$). Over our sample period, in only two cases does this approach require as many as 37 prior trading days to find 22 prior non-POMO trading days; in most other cases, $S_{i,t}^B$ is computed over no longer than six trading weeks prior to a POMO day. Our inference is qualitatively unaffected by employing either longer or shorter trailing intervals for $S_{i,t}^B$. For instance, univariate and multivariate estimates of spread changes on POMO days relative to five-day (one-day) pre-intervention levels — $\overline{\Delta S_{i,t}^B}$, $\gamma_{i,\text{CB}}$, and $\alpha_{i,\text{CB}}$ in Panel A of Table IA-3 (untabulated) — are qualitatively similar to (or even stronger than) those reported in Table 3.

As noted in Section III.A.1 of Pasquariello et al. (2018), daily averaging of intraday bid-ask spreads allows us to mitigate any bias from non-informational microstructure noise in the data (typically salient at the intraday frequency), as well as to account for the unobservable, possibly nonuniform within-day intensity of informed speculation. Both issues may weaken the statistical and economic significance of estimated liquidity externalities of government intervention. With this in mind, we consider here the impact of POMOs on intraday Treasury market liquidity.

Comparing estimates of Treasury market liquidity over portions of POMO days before versus either during or after the ninety-minute Fed Time interval when the FRBNY typically announces and executes its POMOs (10:00 a.m. to 11:30 a.m.; see Section III.B of Pasquariello et al. (2018)) may not be appealing for several reasons. According to Fleming (1997), Treasury bid-ask price spreads are wider in the morning (e.g., until 9:00 a.m.) and afternoon hours (e.g., after 1:30 p.m.) but significantly tighter around Fed Time (e.g., until past 12 p.m.). This significant intraday seasonality makes the estimation of liquidity changes around POMO auctions at Fed Time challenging. In addition, the model of Section II of Pasquariello et al. (2018) predicts that government intervention improves equilibrium market liquidity ($\Delta\lambda \equiv \lambda_{\text{CB}} - \lambda < 0$) under the assumption that all market participants are aware of the presence ($\lambda_{\text{CB}}$) or absence ($\lambda$) of the central bank. It is plausible that a subset of market participants (e.g., the primary dealers bidding at Treasury auctions) may have advance knowledge of an impending POMO auction minutes before its terms are publicly announced at Release Time (10 a.m.).[4] Thus, comparing average measures of Treasury market liquidity within POMO days to those averages within non-POMO days is closer in spirit to the model's notion of $\Delta\lambda$. Lastly, as noted earlier, the effects of POMO auctions on perceived adverse selection risk may display over several hours after their occurrence.

In light of this discussion, as in Sokolov (2009), we compute both average bid-ask spreads $S_{i,t}$ and their benchmark pre-intervention levels $S_{i,t}^{B}$ exclusively over the intraday Fed Time interval. We then run the same univariate and multivariate tests of Section IV.A of Pasquariello et al. (2018) on spread change differentials $\Delta S_{i,t}^{B}$ during Fed Time. As conjectured above, the ensuing estimates of $\overline{\Delta S_{i,t}^{B}}$, $\gamma_{i,\text{CB}}$, and $\alpha_{i,\text{CB}}$, in Panel B of Table IA-3, are nearly always negative (consistent with our model's main prediction) but relatively smaller in magnitude and less often statistically significant than when measured over the entire POMO day (in Table 3).

Studies of the microstructure of equity markets often use percentage bid-ask spreads (Madhavan (2000), Hasbrouck (2007)). Since stock prices are quoted in price per share and there is significant stock price-level heterogeneity and time-series variation, normalizing stocks' bid-ask

[4] For instance, according to Akthar ((1997), p. 48), in the wake of POMOs the Desk has "ongoing contacts with primary dealers [...] about the wide-ranging forces at work in financial markets: changing demands of the dealers' customers in the securities markets and their interest in particular types of securities; [...] dealers' expectations about Treasury financing in the period ahead, and potential customer interest in coming financing."

price spreads, e.g., by the midquote, makes them comparable across stocks and over time. We noted earlier that bid-ask price spreads in the secondary market for Treasury notes and bonds ($S_i$) are quoted as a fraction of their common par value of $1,000. Thus, their averages $S_{i,t}$ are already comparable across Treasury securities and over time. Our inference is nonetheless qualitatively unaffected by using *percentage* bid-ask spreads: $S_i \equiv (A_i - B_i) / \left[\frac{1}{2}(A_i + B_i)\right]$; e.g., Song and Zhu (2018). Panel C of Table IA-3 reports estimates from the univariate and multivariate tests of Section IV.A of Pasquariello et al. (2018) when the dependent variable $\Delta S^B_{i,t}$ is changes in the average daily percentage spread. On-the-run bond price midquotes at all maturities (except at the very long end of the yield curve) tend to be relatively close to par over our sample period. Accordingly, sign and significance of the estimated effect of POMOs on daily percentage bid-ask spreads, $\overline{\Delta S^B_{i,t}}$, $\gamma_{i,\mathrm{CB}}$, and $\alpha_{i,\mathrm{CB}}$ are almost identical to those in Table 3.

## 2.4 Alternative Interpretations

The estimated improvement in Treasury market liquidity accompanying POMOs over the sample period 2001–2007 is unlikely to stem from inventory considerations. The role of inventory management is often invoked in the literature (surveyed in the Introduction) studying central bank interventions in currency markets. According to these studies, government interventions, regardless of their information content, may hinder dealers' ability to provide liquidity to other market participants — e.g., because of inventory targets, stringent capital constraints, "hot potato" effects, or limited risk-bearing capacity.[5] This may ultimately lead to *wider* bid-ask spreads, contrary to the evidence in Table 3.

Inventory considerations may also lead to asymmetric supply effects of POMOs on market liquidity. For instance, the Desk's outright sales (purchases) of notes and bonds — $POMO_{i,t} > 0$ ($POMO_{i,t} < 0$) — may decrease (increase) on-the-run bid-ask spreads by lowering (magnifying) dealers' search costs for sought-after Treasury securities (e.g., Vayanos and Weill (2008), D'Amico and King (2013)). Otherwise, the Desk may concentrate its trading activity on days when Treasury illiquidity is low (e.g., to reduce its security-level transaction costs, as in Song and Zhu (2018)). However, as noted in Sections III.B and IV.A of Pasquariello et al. (2018), the Desk not only did not sell any Treasury security over the sample period 2001–2007, but also explicitly refrained from trading in such scarce and valuable securities as on-the-run Treasury notes and

[5] For instance, in a model of sequential trading under *symmetric* information, Pasquariello (2010) shows that the mere likelihood (yet not the actual occurrence) of large government intervention may induce competitive dealers to *widen* their posted bid-ask spreads to pass all rents from trading with the central bank onto investors, if faced with a prior large imbalance between buyers and sellers of the traded asset.

bonds "so as to avoid adverse market impact" (FRBNY (2005), p. 20), despite their often high liquidity (Fleming (1997), Pasquariello and Vega (2009)).

Alternatively, POMOs may affect liquidity provision in the Treasury bond market by altering reserve market conditions for participating dealers with depository facilities, even if those trades had no discernible impact on the market's information environment (as instead postulated by our model). For example, POMO purchases (sales) may ease (tighten) market-makers' liquidity provision by increasing (decreasing) the availability of credit and capital — i.e., dealers' funding liquidity — ultimately leading to tighter (wider) bid-ask spreads in the Treasury market (e.g., Brunnermeier and Pedersen (2009)). This channel is likely to play a prominent role in correspondence with significant episodes of market turmoil, when credit and capital may be scarce. Yet, this is unlikely to have been the case over our sample period 2001–2007. In addition, the Desk minimizes potential disruptions to the Treasury market by explicitly *avoiding* executing POMOs in days when Treasury auctions, major economic data releases, or other important events for Treasury yields are scheduled (e.g., see FRBNY (2005), (2008)) but market liquidity is often high (Pasquariello and Vega (2007), (2009)). Lastly, and contrary to the predictions of this channel, we noted in Section 2.2 that Treasury market liquidity improves in the wake of *both* numerous POMO purchases and much fewer POMO sales (albeit more weakly) during the financial crisis period 2008–2009 (see Panels B and C of Table IA-2).

To further investigate these possibilities as well as further mitigate omitted variable biases, we consider whether our evidence is robust to explicitly controlling for a variety of additional factors affecting or capturing such conditions as dealers' inventories, pre-auction illiquidity, liquidity provision in the secondary market for Treasury securities, or their relative supply on POMO days. These include changes in overnight repo specialness (the difference between overnight general collateral and on-the-run security-specific repo rates; e.g., Krishnamurthy (2002)), recent Treasury auction results (bid-to-cover ratios and number of days since the latest on-the-run auction; Pasquariello and Vega (2009)), number of days since the latest FOMC meeting (Cieslak, Morse, and Vissing-Jorgensen (2016)), each day's position over the cyclical reserve maintenance period (lasting two weeks, from Thursday [1] to Wednesday [14], during which banks have to keep specified average levels of funds at the Federal Reserve; see Federal Reserve Board of Governors (FRBG) (2005)), the amounts traded by the Desk via temporary open market operations (TOMOs) (Sokolov (2009), Brunetti, di Filippo, and Harris (2011)), most recent pre-POMO illiquidity (average on-the-run bid-ask spreads over the sixty-minute interval immediately before Fed Time, i.e., 9:00 a.m. to 10 a.m. on POMO days, ignoring any prior leakage of auction-level information; Song and Zhu (2018)), the last week of each calendar year (to control for any end-of-year seasonality in policy and trading), and the dates of arguably the most important U.S. macroeconomic and policy announcements (Nonfarm Payroll, Unemployment, Nominal Gross Domestic Product (GDP), Consumer Price Index (CPI), Industrial Production, Housing Starts, and FOMC meetings; e.g., Andersen and Bollerslev (1998), Andersen, Bollerslev, Diebold, and Vega (2003), (2007), Pasquariello and Vega (2007), Brenner, Pasquariello, and Subrahmanyam (2009), and Gilbert, Scotti, Strasser, and Vega (2017)).[6]

We then estimate the multiple regressions of equations (8) and (9) for daily and Fed Time average price and percentage spreads, after including those additional controls, in Panels A to C of Table IA-4, respectively. As conjectured, the resulting estimated POMO intercepts ($\gamma_{i,\mathrm{CB}}$) and dummy coefficients ($\alpha_{i,\mathrm{CB}}$) remain mostly negative and statistically significant, consistent with the model's main prediction.[7] Overall, this evidence suggests that the estimated improvement in Treasury market liquidity in the wake of POMOs in Table 3 is robust to accounting for its pre-auction levels and for such alternative explanations as their impact on dealers' inventory management, on the relative supply of the traded securities, or on reserve market conditions for liquidity providers.

[6] Some of these variables may also be affected by POMO auctions, as well as affect the extent of uncertainty among market participants about the Desk's POMOs. As noted in Section II.B of Pasquariello et al. (2018) and Conclusion 1, the positive liquidity externality of government intervention in our model is increasing in market participants' perceived uncertainty about the central bank's policy target ($\sigma_T^2$). In Section IV.C.3 of Pasquariello et al. (2018), we provide evidence of this relationship with a more direct proxy for POMO policy uncertainty.

[7] OLS same-POMO intercepts $\gamma_{i,\mathrm{CB}}$ for 10-year Treasury notes and 30-year Treasury bonds in Table IA-4 should be interpreted with caution, since they are estimated over a relatively small number of events while accounting for a relatively large number of control variables.

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## Table IA-1. POMOs and Market Liquidity: Sample-Specific Issues

Table IA-1 reports means of daily bid-ask price spread changes $\overline{\Delta S^B_{i,t}}$ (in bps) and OLS estimates of $\gamma_{i,\text{CB}}$ and $\alpha_{i,\text{CB}}$ from equations (8) and (9) for on-the-run Treasury notes and bonds and *same*-maturity or *any*-maturity POMOs (as in Table 3) over the earlier BrokerTec subsample (Jan. 1, 2001 to Dec. 31, 2004; Panel A), the later BrokerTec subsample (Jan. 1, 2005 to Dec. 31, 2007; Panel B), and the full GovPX sample period (Jan. 1, 2001 to Dec. 31, 2004; Panel C). $N$ is the number of observations. $R^2_a$ is the adjusted $R^2$. A *, **, or *** indicates statistical significance at the 10%, 5%, or 1% levels, respectively, using Newey-West standard errors for $\alpha_{i,\text{CB}}$.

| | *Same-maturity POMOs* | | | | | | *Any-maturity POMOs* | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Segment | $\overline{\Delta S^B_{i,t}}$ | $\gamma_{i,\text{CB}}$ | $N$ | $\alpha_{i,\text{CB}}$ | $R^2_a$ | $N$ | $\overline{\Delta S^B_{i,t}}$ | $\gamma_{i,\text{CB}}$ | $N$ | $\alpha_{i,\text{CB}}$ | $R^2_a$ | $N$ |
| *Panel A. BrokerTec: 01/2001–12/2004* | | | | | | | | | | | | |
| 2-year | -0.172*** | -0.373*** | 114 | -0.116*** | 12% | 973 | -0.184*** | -0.373*** | 149 | -0.126*** | 14% | 973 |
| 3-year | -0.091** | -0.046** | 24 | 0.035 | 20% | 407 | -0.183*** | -0.336*** | 45 | -0.027 | 21% | 407 |
| 5-year | -0.328*** | -0.715*** | 49 | -0.216** | 14% | 977 | -0.350*** | -0.673*** | 148 | -0.212*** | 17% | 977 |
| 10-year | -0.107 | 0.109 | 21 | -0.036 | 14% | 855 | -0.533*** | -0.816*** | 134 | -0.377*** | 16% | 855 |
| 30-year | -0.821 | -0.710 | 19 | -0.348 | 9% | 804 | -1.096*** | -1.000*** | 138 | -0.671* | 9% | 804 |
| *Panel B. BrokerTec: 01/2005–12/2007* | | | | | | | | | | | | |
| 2-year | -0.0002 | -0.0005 | 43 | 0.0001 | 12% | 709 | -0.0003 | -0.0005 | 62 | -0.0004 | 11% | 709 |
| 3-year | -0.014*** | -0.011*** | 34 | -0.007 | 22% | 557 | -0.011*** | -0.009*** | 57 | -0.004 | 23% | 557 |
| 5-year | -0.003 | -0.003 | 26 | -0.003 | 23% | 709 | -0.003* | -0.003* | 62 | -0.004 | 23% | 709 |
| 10-year | -0.017** | -0.016*** | 12 | -0.007 | 15% | 708 | -0.004 | -0.005 | 62 | -0.004 | 14% | 708 |
| 30-year | -0.107* | -0.125* | 9 | -0.093** | 16% | 712 | -0.069*** | -0.074*** | 62 | -0.049* | 17% | 712 |
| *Panel C. GovPX: 01/2001–12/2004* | | | | | | | | | | | | |
| 2-year | -0.208*** | -0.306*** | 117 | -0.159*** | 8% | 984 | -0.209*** | -0.213*** | 153 | -0.173*** | 9% | 984 |
| 3-year | -0.312 | -0.004 | 23 | -0.299 | 13% | 345 | -0.504* | -0.453 | 44 | -0.510* | 15% | 345 |
| 5-year | -0.061 | -0.373*** | 49 | -0.013 | 3% | 939 | -0.307*** | -0.314*** | 152 | -0.243** | 4% | 939 |
| 10-year | -0.349 | -0.362 | 22 | -0.237 | 3% | 848 | -0.490** | -0.390 | 148 | -0.421** | 4% | 848 |
| 30-year | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |

Table IA-2. POMOs and Market Liquidity: The 2008 Financial Crisis

Table IA-2 reports means of daily bid-ask price spread changes $\overline{\Delta S^B_{i,t}}$ (in bps) and OLS estimates of $\gamma_{i,CB}$ and $\alpha_{i,\mathrm{CB}}$ from equations (8) and (9) for on-the-run Treasury notes and bonds and *same*-maturity or *any*-maturity POMOs (as in Table 3) over the extended BrokerTec subsample (Jan. 1, 2001 to Dec. 31, 2009; Panel A) and the crisis BrokerTec subsample (Jan. 1, 2008 to Dec. 31, 2009) for POMO purchases (Panel B) and POMO sales (Panel C). $N$ is the number of observations. $R^2_a$ is the adjusted $R^2$. A $^*$, $^{**}$, or $^{***}$ indicates statistical significance at the 10%, 5%, or 1% levels, respectively, using Newey-West standard errors for $\alpha_{i,\mathrm{CB}}$.

| | *Same-maturity POMOs* | | | | | | *Any-maturity POMOs* | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Segment | $\overline{\Delta S^B_{i,t}}$ | $\gamma_{i,\mathrm{CB}}$ | $N$ | $\alpha_{i,\mathrm{CB}}$ | $R^2_a$ | $N$ | $\overline{\Delta S^B_{i,t}}$ | $\gamma_{i,\mathrm{CB}}$ | $N$ | $\alpha_{i,\mathrm{CB}}$ | $R^2_a$ | $N$ |
| *Panel A. BrokerTec: 01/2001–12/2009* | | | | | | | | | | | | |
| 2-year | -0.104$^{***}$ | -0.257$^{***}$ | 189 | -0.071$^{***}$ | 7% | 2,151 | -0.099$^{***}$ | -0.255$^{***}$ | 282 | -0.066$^{***}$ | 8% | 2,151 |
| 3-year | -0.046$^{*}$ | -0.115$^{**}$ | 58 | 0.013 | 11% | 964 | -0.087$^{***}$ | -0.257$^{***}$ | 102 | -0.023 | 11% | 964 |
| 5-year | -0.151$^{**}$ | -0.466$^{***}$ | 113 | -0.085$^{*}$ | 8% | 2,157 | -0.192$^{***}$ | -0.472$^{***}$ | 281 | -0.109$^{***}$ | 11% | 2,155 |
| 10-year | -0.056 | -0.016 | 53 | 0.061 | 8% | 2,034 | -0.275$^{***}$ | -0.663$^{***}$ | 267 | -0.170$^{**}$ | 9% | 2,032 |
| 30-year | -0.538 | -1.040 | 43 | -0.064 | 11% | 1,981 | -0.660$^{**}$ | -1.144$^{***}$ | 270 | -0.293 | 12% | 1,979 |
| *Panel B. BrokerTec: 01/2008–12/2009, POMO Purchases* | | | | | | | | | | | | |
| 2-year | -0.007 | -0.007 | 19 | 0.001 | 1% | 469 | -0.009$^{***}$ | -0.010$^{***}$ | 56 | -0.015 | 12% | 469 |
| 3-year | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |
| 5-year | -0.023$^{***}$ | -0.029$^{***}$ | 32 | -0.001 | 3% | 471 | -0.027$^{***}$ | -0.034$^{***}$ | 56 | -0.038$^{*}$ | 21% | 469 |
| 10-year | -0.026$^{**}$ | -0.012 | 19 | 0.012 | 0% | 471 | -0.030$^{***}$ | -0.022 | 56 | -0.135$^{*}$ | 23% | 469 |
| 30-year | -0.439$^{***}$ | -0.312$^{**}$ | 15 | -0.144 | 22% | 465 | -0.454$^{***}$ | -0.256$^{***}$ | 56 | -0.850$^{**}$ | 48% | 469 |
| *Panel C. BrokerTec: 01/2008–12/2009, POMO Sales* | | | | | | | | | | | | |
| 2-year | 0.001 | -0.003 | 13 | 0.013 | 1% | 469 | -0.002 | -0.006 | 15 | -0.010 | 12% | 469 |
| 3-year | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |
| 5-year | -0.022 | -0.014 | 6 | 0.016 | 3% | 471 | -0.023$^{*}$ | -0.018 | 15 | -0.041$^{**}$ | 21% | 469 |
| 10-year | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | -0.011 | -0.004 | 15 | -0.097 | 22% | 469 |
| 30-year | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | -0.190 | -0.310 | 14 | -0.406 | 47% | 469 |

## Table IA-3. POMOs and Market Liquidity: Alternative Specifications

Table IA-3 reports means of daily bid-ask price spread changes $\overline{\Delta S^B_{i,t}}$ (in bps) and OLS estimates of $\gamma_{i,\mathrm{CB}}$ and $\alpha_{i,\mathrm{CB}}$ from equations (8) and (9) for on-the-run Treasury notes and bonds and *same*-maturity or *any*-maturity POMOs (as in Table 3) over the basic BrokerTec sample period (Jan. 1, 2001 to Dec. 31, 2007) when computing $\Delta S^B_{i,t}$ relative to past *five* non-POMO days (Panel A), over the *90*-minute POMO auctions' *Fed Time* (10:00 a.m. to 11:30 a.m. ET; Panel B), or from *percentage* bid-ask spreads (Panel C). $N$ is the number of observations. $R^2_a$ is the adjusted $R^2$. A *, **, or *** indicates statistical significance at the 10%, 5%, or 1% levels, respectively, using Newey-West standard errors for $\alpha_{i,\mathrm{CB}}$.

| | *Same-maturity POMOs* | | | | | | *Any-maturity POMOs* | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Segment | $\overline{\Delta S^B_{i,t}}$ | $\gamma_{i,\mathrm{CB}}$ | $N$ | $\alpha_{i,\mathrm{CB}}$ | $R^2_a$ | $N$ | $\overline{\Delta S^B_{i,t}}$ | $\gamma_{i,\mathrm{CB}}$ | $N$ | $\alpha_{i,\mathrm{CB}}$ | $R^2_a$ | $N$ |
| *Panel A. BrokerTec: 01/2001–12/2007, Five-day Benchmark Window* | | | | | | | | | | | | |
| 2-year | -0.110*** | -0.267*** | 157 | -0.084*** | 5% | 1,682 | -0.110*** | -0.263*** | 211 | -0.083*** | 5% | 1,682 |
| 3-year | -0.034* | -0.062* | 58 | -0.008 | 5% | 964 | -0.065*** | -0.193*** | 102 | -0.039** | 5% | 964 |
| 5-year | -0.248*** | -0.635*** | 75 | -0.198*** | 6% | 1,686 | -0.225*** | -0.510*** | 210 | -0.160*** | 7% | 1,686 |
| 10-year | -0.111 | -0.785 | 33 | -0.075 | 3% | 1,563 | -0.270** | -0.581*** | 196 | -0.188** | 4% | 1,563 |
| 30-year | -0.381 | -0.116 | 28 | -0.120 | 2% | 1,516 | -0.662*** | -1.239*** | 200 | -0.518** | 3% | 1,516 |
| *Panel B. BrokerTec: 01/2001–12/2007, Fed Time* | | | | | | | | | | | | |
| 2-year | -0.124*** | -0.309*** | 157 | -0.082** | 5% | 1,682 | -0.115*** | -0.285*** | 211 | -0.072** | 5% | 1,682 |
| 3-year | -0.036 | -0.098 | 58 | -0.010 | 6% | 964 | -0.058*** | -0.177*** | 102 | -0.009 | 6% | 964 |
| 5-year | -0.213 | -0.607** | 75 | -0.149 | 4% | 1,686 | -0.249*** | -0.607*** | 210 | -0.154*** | 7% | 1,686 |
| 10-year | -0.099 | -0.236 | 33 | -0.019 | 4% | 1,563 | -0.349** | -0.819*** | 196 | -0.246** | 5% | 1,563 |
| 30-year | -0.216 | -0.380 | 28 | -0.004 | 2% | 1,516 | -1.021*** | -1.820*** | 200 | -0.840** | 3% | 1,516 |
| *Panel C. BrokerTec: 01/2001–12/2007, Percentage Spread* | | | | | | | | | | | | |
| 2-year | -0.124*** | -0.305*** | 157 | -0.085*** | 8% | 1,682 | -0.129*** | -0.313*** | 211 | -0.089*** | 9% | 1,682 |
| 3-year | -0.046** | -0.114** | 58 | 0.013 | 11% | 964 | -0.088*** | -0.254*** | 102 | -0.023 | 11% | 964 |
| 5-year | -0.205*** | -0.574*** | 75 | -0.137* | 8% | 1,686 | -0.239*** | -0.564*** | 210 | -0.148*** | 12% | 1,686 |
| 10-year | -0.059 | 0.067 | 33 | 0.040 | 9% | 1,563 | -0.349*** | -0.728*** | 196 | -0.251*** | 10% | 1,563 |
| 30-year | -0.524 | -1.169 | 28 | -0.267 | 6% | 1,516 | -0.642*** | -0.995*** | 200 | -0.471* | 6% | 1,516 |

## Table IA-4. POMOs and Market Liquidity: Controls

Table IA-4 reports OLS estimates of $\gamma_{i,\mathrm{CB}}$ and $\alpha_{i,\mathrm{CB}}$ for on-the-run Treasury notes and bonds and *same*-maturity or *any*-maturity POMOs (as in Table 3) over the basic BrokerTec sample period (Jan. 1, 2001 to Dec. 31, 2007), after augmenting equations (8) and (9) with additional control variables for Treasury market conditions (see Section 2.4), for changes in average *daily* bid-ask *price* spreads (Panel A), *Fed Time* bid-ask price spreads (Panel B), and daily *percentage* bid-ask spreads (Panel C). $N$ is the number of observations. $R_a^2$ is the adjusted $R^2$. A *, **, or *** indicates statistical significance at the 10%, 5%, or 1% levels, respectively, using Newey-West standard errors for $\alpha_{i,\mathrm{CB}}$.

| | *Same-maturity POMOs* | | | | | *Any-maturity POMOs* | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Segment | $\gamma_{i,\mathrm{CB}}$ | $N$ | $\alpha_{i,\mathrm{CB}}$ | $R_a^2$ | $N$ | $\gamma_{i,\mathrm{CB}}$ | $N$ | $\alpha_{i,\mathrm{CB}}$ | $R_a^2$ | $N$ |
| *Panel A. BrokerTec: 01/2001–12/2007, with Controls* | | | | | | | | | | |
| 2-year | -1.155*** | 157 | -0.050** | 36% | 1,682 | -1.318*** | 211 | -0.056*** | 37% | 1,682 |
| 3-year | -0.112 | 58 | 0.012 | 38% | 964 | 0.136 | 102 | -0.004 | 38% | 964 |
| 5-year | -1.685* | 75 | -0.071 | 33% | 1,686 | -1.466*** | 210 | -0.081** | 36% | 1,686 |
| 10-year | -1.254 | 33 | 0.074 | 37% | 1,563 | -1.705*** | 196 | -0.108** | 39% | 1,563 |
| 30-year | -7.998 | 28 | -0.057 | 31% | 1,516 | -5.345*** | 200 | -0.209 | 34% | 1,516 |
| *Panel B. BrokerTec: 01/2001–12/2007, Fed Time, with Controls* | | | | | | | | | | |
| 2-year | -0.959*** | 157 | -0.061** | 24% | 1,682 | -1.253*** | 211 | -0.054* | 23% | 1,682 |
| 3-year | 0.380 | 58 | -0.009 | 29% | 964 | -0.526*** | 102 | -0.011 | 30% | 964 |
| 5-year | -1.791* | 75 | -0.080 | 20% | 1,686 | -1.547*** | 210 | -0.114*** | 22% | 1,686 |
| 10-year | -1.964 | 33 | 0.040 | 24% | 1,563 | -2.140*** | 196 | -0.110 | 26% | 1,563 |
| 30-year | -7.273 | 28 | 0.837 | 24% | 1,516 | -5.067*** | 200 | -0.485* | 26% | 1,516 |
| *Panel C. BrokerTec: 01/2001–12/2007, Percentage Spread, with Controls* | | | | | | | | | | |
| 2-year | -1.148*** | 157 | -0.048** | 35% | 1,682 | -1.257*** | 211 | -0.051** | 35% | 1,682 |
| 3-year | -0.436** | 58 | 0.008 | 35% | 964 | -0.092 | 102 | -0.010 | 35% | 964 |
| 5-year | -1.439** | 75 | -0.063 | 34% | 1,686 | -1.351*** | 210 | -0.073** | 36% | 1,686 |
| 10-year | -0.556 | 33 | 0.078 | 34% | 1,563 | -1.086** | 196 | -0.101* | 34% | 1,563 |
| 30-year | -5.464 | 28 | 0.110 | 31% | 1,516 | -4.337*** | 200 | -0.075 | 33% | 1,516 |