Does Public Latency Influence Market Quality? An Analysis of Pre-trade Transparency at the Taiwan Futures Exchange

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ABSTRACT

In order to smooth out the trading process and to offer customers real-time information, the 'electronic trading system' (ETS) on the Taiwan Futures Exchange (TAIFEX) has increased the frequency of market information updates and shortened the quote display time interval in the electronic open book on three separate occasions from the initial five-second period, to three seconds on 6 March 2006, one second on 28 January 2008, and a quarter of a second on 31 August 2009. A series of IT upgrades by TAIFEX provides a unique opportunity to test empirically the impact of public latency on market quality. According to the analyses of the around event without contamination by the sub-prime financial crisis and structure changes, our findings indicate a persistent decrease both in spread and transient volatility, and a persistent increase in depth in the period following the continuous reduction in the public latency. These results suggest that an increase pre-trade transparency by continuously updating order book information dissemination technology systems in millisecond trading environment can improve market quality.

Keywords: Public latency; Pre-trade transparency; Refresh interval; Algorithmic trading; Millisecond trading environment.

1. Introduction

Stock and futures exchanges around the world have been investing heavily in upgrading their systems to reduce the time it takes to send information to customers as well as to accept and handle customers' orders. In the past years, the 'electronic trading system' (ETS) on the Taiwan Futures Exchange (TAIFEX) has increased the frequency of market information updates and shortened the quote display time interval in the electronic open book, as a result of the three reductions in the electronic open book refresh interval from the initial five-second period, to three seconds on 6 March 2006, one second on 28 January 2008, and a quarter of a second on 31 August 2009, allows traders observe more "timely" information from limit order book in a fixed time interval.

The purpose of this study is to examine how publicly revealing mass information stemming from continuously enhancing refresh rate of limit order book affects market quality. Particularly, this paper focuses on the increased pre-trade transparency through the disclosure speed ability of limit order book, since the disclosure policy allows traders observe more updating information from limit order book in a fixed time interval.

The effect of transparency on market quality is important, and has generated strong interest among academics, practitioners and regulators. For example, Boehmer, Saar, and Yu (2005) study market transparency by looking at the introduction of NYSE's OpenBook service that provides limit-order book information to traders off the exchange floor. They find that an increase in market transparency affects investors' trading strategies and can improve certain dimensions of market quality. Baruch (2005) construct model to address the question of how revealing more or less information about the content of limit order book affects the market. They find that increased pre-trade transparency through the disclosure speed ability of limit order book allows traders observe more updating information from limit order book in a fixed time interval. Eom, Ok, and Park (2007) examine the effect of the introduction of two discrete changes in its disclosure policy about the specified number of the best buy and sell prices and the number of shares desired or offered at those prices. They indicate that market quality is increasing and concave in pre-trade transparency. Aït-Sahalia and Saglam (2013) find that lower latency generates higher profits and higher liquidity provision.

However, Budish, Cramton and Shim (2013) argue that the ability to continuously update order books generates technical arbitrage opportunities and a wasteful arms race in which fundamental investors bear costs through larger spreads and thinner markets. Han, Khapko and Kyle (2014) suggest that since fast market makers can cancel quotes faster than slow traders, this causes a winner's curse resulting in higher spreads. Hasbrouck and Saar (2013) argue that low public latency could lead to a situation whereby the execution risk caused by high-speed changes in quotes may not be diversifiable, with slower traders always losing to faster traders. Stiglitz (2014) doubt that high frequency quotation is welfare improving and makes a case for slower markets.

In this study, we focus on a particular form of pre-trade transparency:[1] the ability of market participants to observe the pending trading interests of other participants. Our measure of pre-trade transparency is defined as the disclosure speed of public limit order book. The time between the limit order book refresh intervals is the 'public latency' of the exchange, which should generally be dependent upon the trading speed limitations for all market participants, although professional traders can enhance their involvement in low latency trading by privately investing in millisecond trading facilities which can result in their low latency trading being lower than that of other individual investors.

An important question is who benefits from such low public latency. The millisecond environment involves activities by market traders to implement their trading strategies in response to market news. Thus, disclosure speed is a critical element in the adjustment of traders' order strategies, since it improves the profitability of such strategies. The decrease in public latency of limit order book enables traders not only to update bid and order prices faster in response to incoming orders, but also to see how their order strategies affect the book. Quickly receiving the pending trading interests of other participants can be promptly decoded to refine one's reservation value of a security to maximize profits and to resiliently adjust order strategy to minimize the risks of adverse selection and non-execution.

Further, low public latency means that quotes are more informative because of the speed with which they reflect information. By more closely monitor the market for transitory price deviations and to trade and place orders to profit these short-term deviations, sophisticated investors or institutional investors (informed investors) may be better able to rebalance their positions in securities affected by arrival of

[1] Madhavan, Porter, and Weaver (2005) defined that pre-trade transparency refers to the dissemination of current bid and ask quotations, depths, and information about limit orders away from the best prices. Post-trade transparency refers to the public and timely transmission of information on past trades, including execution time, volume, and price. Hence, we expected that the technological changes of public latency in this paper, being related to transaction times, also affected post-trade transparency. However, since it is restricted by the paper length, we focus on the pre-trade transparency.

fundamental information.

Liquidity providers (uninformed traders) also prefer fast disclosure and if possible they are more likely to pay brokers/dealers extra to get low latency service. An increase in market transparency in terms of refresh rate of limit order book enables them to immediately adjust their orders by rapidly obtaining immediacy, or to slowly provide liquidity, which reduces the adverse selection costs.[2] By adding and cancelling orders to the limit order book, they can use quote updates to manage their intraday risk. Baruch and Glosten (2013) argue that high-speed updates represent the provision of liquidity and, on average, allow for information to be reflected in prices.

While the effect of transparency on market quality has been extensively examined in the finance literature, there are few studies in market design relating to disclosure speed for pre-trade transparency. We explore whether disclosure policy change improves market quality. The timing for scalpers, day-traders and high-frequency algorithmic trading programs, with regard to getting in and out of the market, is totally reliant upon the rapid flow of numbers through the screen. Low public latency make self-management of orders more appealing to market participants since market participants are able to adjust their trading strategies more rapidly than ever before based upon the vastly improved latency from the frequency of updated information. As argued by Demos and Goodhart (1996), the refresh rate of on-screen information relating to the limit book plays a crucial role in each transaction because the numbers of observations within a specific time interval (calendar time) could be a determinant variable of both intraday volatility and spread. The efforts made by exchanges are invariably aimed at promoting market liquidity and efficiency, and indeed, we regard the higher performance of trading platforms (delivering more rapid, fluent 'trade and quote' (TAQ) traffic communication to the market) as a significant improvement in market pre-trade transparency, ultimately leading to enhanced market quality.

Our investigation, which is most closely related to empirical research approach of Madhavan et al. (2005), Boehmer et al. (2005) and Eom, Ok, and Park (2007), uses high-frequency intraday data on the Taiwan Stock Exchange Capitalization Weighted Stock Index (TAIEX) futures. We have three findings from stepwise

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[2] Recent theoretical and empirical studies suggest that limit orders may be motivated by informed trading aimed at avoiding the release of private information, whilst market orders may be motivated by uninformed trading aimed at avoiding picking-off losses; see, for example: Seppi (1997), Bloomfield, O'Hara and Saar (2005), Anand, Chakravarty and Martell (2005), Goettler, Parlour and Rajan (2005) Foucault, Kadan and Kandel (2005) and Kaniel and Liu (2006).

excluding market contamination: (1) our findings indicate inverse U-shaped curves for spread and U-shaped curves for both depth and transient volatility in the period following the reduction in the public latency. (2) According to the full sample analyses without contamination by the sub-prime financial crisis, we find that spread, depth and transient volatility are negatively associated with low public latency. (3) Examining the analyses of the around event without contamination by the structure changes in long run, our findings indicate a persistent decrease both in spread and transient volatility, and a persistent increase in depth in the period following the continuous reduction in the public latency. We suggest that multiple levels of increased market pre-trade transparency from persistent rule changes of public latency could result in the improved evolution of liquidity and the reduced transient volatility. Our analyses of the change in liquidity and transient volatility around use several econometric tests to implement controls and account for potential estimation problems.

The evidence we present contribute to recent literature in several ways. First, the theoretical and empirical literature provides some conflicting predictions on how market quality would change when exchanges start to increase quote content of limit order book, and our results are in view of updating speed of limit order book to analyze the influence of pre-trade transparency on liquidity and transient volatility. Second, most of international exchanges have repeatedly emphasized the need for increased pre-trade transparency by enhancing refreshing rate of their screen-based information. Our research is the first empirical study to provide support for such disclosure speed policy. Third, prior studies focus on the impact of one-time change of market design on market quality. Our research shows that a series of monotonically persistent changes of market design exerts influence on market quality. A series of the same regulation changes are able to capture the variation of identical property of pre-trade transparency. Fourth, we can obtain a clear non-liner evidence by analyzing the pure marginal effects in the multiple level of pre-trade transparency, since our research is based on the initial five-second period, to three seconds, one second, and a quarter of a second of limit order book updating speed. As such, research on market design can help exchanges and regulators improve the functioning of financial markets.

The remainder of this paper is organized as follows. Section 2 presents a review of the extant literature assisting in the development of our hypotheses, followed in Section 3 by an introduction to the institution of the TAIFEX, the rule changes and the sample data used in this study. The empirical results are provided in Section 4. Finally, discussions of the findings of this study are presented in Section 5.

2. Literature review and hypotheses development

2.1 Related literature

Boehmer, Saar and Yu (2005) study pre-trade transparency by looking at the introduction of NYSE's OpenBook service that provides limit-order book information. They find that greater pre-trade transparency of the limit order book is a win-win situation. Anand, Chakravarty and Martell (2005) and Bloomfield, O'Hara and Saar (2005) provide the empirical and experimental researches for the evolution of liquidity formed by informed and uninformed traders. The evolution of liquidity from trading speed adjustments of informed and uninformed traders' strategies could substantially change the measures of market quality, such as spread, depth and transient volatility. Glosten (1999) documents that increased transparency leads to greater commonality of information, and then changes order strategies of market participants, which can alter characteristics of the market environment, such as liquidity and informational efficiency. Conrad, Wahal and Xiang (2014) find that higher quotation activity is associated with price series that more closely resemble a random walk, and significantly lower cost of trading.

As regards price efficiency, Anderson, Cooper and Prevost (2006) conclude that price elasticity responded to block trades based upon the speed of arrival of limit orders. Boehmer et al. (2005), Baruch (2005) and Hendershott and Moulton (2011) also find that with greater transparency, there was a corresponding reduction in market order execution time, and more efficient price adjustments. Easley, Hendershott and Ramadorai (2009) and Riordan and Storkenmaier (2011) examine the impact of lower latency trading on liquidity, turnover and returns and find that leveling the playing field between the public and intermediaries leads to higher liquidity.

In contrast, Madhavan et al. (2005) find that following the introduction of a computerized system, known as 'Market by Price', market quality was changed under both floor and automated trading systems the Toronto Stock Exchange. In direct contradiction to the general beliefs amongst regulators, they conclude that greater market transparency diminished liquidity and raised both volatility and the costs of immediacy. By examining of the Sydney Futures Exchange, Bortoli, Frino, Jarnecis and Johnstone (2006) reveal that the degree of disclosure provided by the limit order book is capable of changing the trading behavior of investors. They find a corresponding increase in quoted spreads and reductions in depth at the best quotes. The same conclusion is also reported by Bloomfield and O'Hara (1999), Madhaven et al. (2005) and Lescourret and Robert (2011). Ángels De Frutos and Manzano (2002) also find that liquidity may be diminished when markets are more transparent.

Aitken, Berkman and Mak (2001) point out that the enhancement in market transparency, through tightening the undisclosed order regulation on the Australian Stock Exchange, results in a significant decline in trading volume.

In sum, the improvement of an increase in market transparency by reducing latency on market quality is still inconclusive.

2.2 Hypotheses

In this section, we develop our hypotheses. We propose that low public latency could increase transparency of the quote and transaction process and thus improve market quality. Glosten (1999) presents an informal argument stating that increased transparency should lead to greater commonality of information, implying more efficient prices and narrower spreads. Chun and Chuwonganant (2009) also find that with greater market transparency, there was lower return volatility. Hasbrouck and Saar (2011) show that increased low-latency activity improved traditional market quality measures, such as spreads, displayed depth and transient volatility in the limit order book[3]. The decrease in latency could improve market quality by allowing investors to update bid and offer prices faster in response to incoming orders. Baruch and Glosten (2013) argue that high-speed quote updates represent the provision of liquidity and allow for information to be reflected in prices. Realized spreads could decline because increased competition between liquidity providers provides incentives to update quotes. Conrad, Wahal and Xiang (2014) argue that high-frequency quotations could reduce effective spreads. Reduction in effective spreads could be attributed to lower revenue for liquidity providers (lower realized spreads) or smaller losses to informed trades (changes in price impact), either because of a change in the information environment, or because liquidity providers are less likely to be adversely selected. We therefore propose the following hypotheses.

Hypothesis 1: *Increased public low-latency reduces spread width.*

Hypothesis 2: *Increased public low-latency increases quote depth.*

Hypothesis 3: *Increased public low-latency reduces transient volatility.*

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[3] A few other related latency topics are also pursued in the prior studies; for example, Barclay, Hendershott and McCormick (2003) argue that informed traders would benefit from the more rapid order execution speed on an electronic trading platform. In their subsequent examination of the differences in the information transmitted by geographical location, Garvey and Wu (2010) find that traders close to the New York City area would take advantage of order execution. Their findings highlighted the importance of latency to competitive market participants. The model presented by Moallemi and Săglam (2010) model provided a closed-form expression for latency costs in terms of the well-known parameters of the underlying asset.

3. Market structure and data

3.1. Background to the structure of the TAIFEX and the limit order book refresh interval

The TAIFEX is a continuous auction market which accepts market and limit orders for futures contracts, matching these client orders by a price-time priority trading principle where market orders are more privileged than limit orders. As an emerging market, trading activity on the TAIFEX comprises mainly of individual investors and futures proprietary traders.[4] As shown in Figure 1, the proportion of individual investors involved in market activities on the TAIFEX in 2010 represented a substantial share (47.88 per cent), a situation which differs enormously from other developed markets.

<Figure 1 is inserted about here>

The TAIFEX publicly discloses a five number of the best buy and sell prices and the number of shares desired or offered at those prices for all market participants. In order to smooth out the trading process and to offer customers real-time information for high transparency, the 'electronic trading system' (ETS) on the TAIFEX has increased the frequency of market information updates and shortened the quote display time interval in the electronic open book on three separate occasions (from the initial five-second period, to three seconds on 6 March 2006, one second on 28 January 2008, and a quarter of a second on 31 August 2009).[5] Undoubtedly, the disclosure policy is able to disseminate more information of limit order book in a fixed time to the market, and it allows us to address the effect of pre-trade transparency on market quality. Besides, TAIEX futures are the most liquid equity futures product traded on the TAIFEX. We can see from the contract specifications in Table 1 that a total of 24 million lots were traded in 2009, at an average daily trading volume of 98,108 contract lots. In order to acquire the greatest number of transaction and quote data for our market microstructure study, we select the nearest month contract until expiry.

<Table 1 is inserted about here>

3.2. Data sample

Intraday ultra-high-frequency TAQ datasets covering the period from 3 May

[4] According to Futures Industry Association (FIA) trading volume statistics in *2009 Derivatives Exchange Volume, An Interactive Discussion*, the TAIFEX ranks eighteenth based on futures and options contracts traded in 2009, with a total of 135 million lots.

[5] The details are in the Taiwan Futures Market Development 2009 Report.

2005 to 17 June 2010 are selected for this study; these datasets, which are produced by the Taiwan Economic Journal (TEJ), provide a total of 1,241 trading days for analysis. Any errors in the raw data are subsequently filtered out, including data on transactions after trading hours, and observations with missing values; 13,000 observations were ultimately excluded from the sample, resulting in a final total of tick-by-tick market data observations in excess of 58 million for analysis in this study.

The dependent variables are classified by dimensions of market quality, such as spread, depth and transient volatility, the definitions as: Q_b (Q_a) is the best bid (ask) quote; *QSpread* is the quoted spread, which is equal to $Q_a - Q_b$; *R_QSpread* is the relative quoted spread which is equal to $100 \times$ *QSpread*/mid-quote; *EffSpread* is the effective spread, which is equal to $I \times 2 \times$(transaction price – mid-quote) where I =1 when buyer initiated, and –1 when seller initiated; *R_EffSpread* is the relative effective spread, which is equal to $100 \times$ *EffSpread*/mid-quote; *Depth* is the sum of the waiting limit orders at the best bid and ask quote prices; *DepthBid* (*DepthAsk*) is the number of waiting limit orders at the best bid (ask) quote price; *R_Depth* is the relative depth of the best quote, which is equal to $100 \times$ (*DepthBid* – *DepthAsk*)/*Depth*; $Volatility_{15}$ is the standard deviation of mid-quote returns during a fifteen minute interval. The control variables could capture the market trading environments, and the definitions as: $N\text{-}Trade_{15}$ is the number of transactions during a fifteen minute interval; *Volume* is the total number of daily transactions; *HiLow* is the highest minus the lowest transaction daily prices; and *Price* is the daily closing price.

4. Empirical results

4.1. The full sample analyses

Our primary concern in this study is the acceleration of public latency as a result of the changes in the limit order book refresh interval, with the design of the dummy variables enabling us to capture the additive effects of increases in the refresh rate. The dummy variables used in our regression for the full sample analyses (shown in Table 2) are constructed according to the rule change dates. Furthermore, we isolate contamination by the financial crisis occurring during our sample period (as a result of the market crash attributable to the sub-prime mortgage crisis) by dividing the overall period into two sub-periods, the pre- and post-sub-prime crisis periods. The sub-prime crisis period is defined as the time from the conservatorship of IndyMac Bank to the bankruptcy of General Motors (1 July 2008 to 31 May 2009); thus, the pre-sub-prime crisis period runs from 3 May 2005 to 30 June 2008, and the post-sub-prime crisis period runs from 1 June 2009 to 17 June

2010.

<Table 2 is inserted about here>

The summary statistics of all of the market variables of full sample data for the nearest-month TAIEX futures are provided in Table 3, which provides mean values and standard deviations of the dependent variables and control variables for all of the regression models. According to the F-test for the equal means, the market quality variables and control variables differ significantly across the four periods under examination, which implies differences in overall market quality for the four different limit order book refresh intervals. We find that the most of spread variables and transient volatility display inverse U-shaped curves from period 1 to period 4, whereas the most of depth variables display U-shaped curves from period 1 to period 4. This findings show that the market quality is significantly associated with public latency.

<Table 3 is inserted about here>

Bid-ask spread

It is clearly easier for futures exchange traders to run their strategies in a more liquid trading environment; indeed, all market participants desire to trade in a highly liquid market in order to reduce the execution costs, and when choosing to enter or exit a market, the bid-ask spread should indeed be considered by liquidity takers be an execution cost (paying more than they expected to close a deal). We test the relationship of bid-ask spread and public latency by modifying the regression models of Madhaven et al (2005) and Boehmer et al. (2005), using control variables to reflect market trading activity on each trading day. The regression model for the full sample period is as follows:

$$Spread_t(QSpread_t, R\_QSpread_t, EffSpread_t, R\_Effspread_t) \\ = \alpha_0 + \alpha_1 D_1 + \alpha_2 D_2 + \alpha_3 D_3 + \alpha_4 Volume_t + \alpha_5 HiLow_t + \alpha_6 \mathrm{Pr}ice_t + \varepsilon_t \quad (1)$$

The results of the regressions for the full sample period are reported in Panel A of Table 4. Of considerable importance is the fact that, according to the coefficient signs of the intercept, D_1, D_2 and D_3, *QSpread*, *R_QSpread* and *R_EffSpread* variables exhibit an inverse U-shaped curve over our sample period, and *EffSpread* exhibits an persistently decreasing over our sample period. The relationship between low latency and quoted spread is found to be positive prior to a specific break point in the third period, and eventually be negative. We argue that the market transparency from a persistent single kind of rule changes as the reduction in quote display refresh rate has a non-linear effect on spread, which could strengthen the evolution evidences of spread in multiple levels of market transparency.

<Table 4 is inserted about here>

The results presented in Panel A of Table 4 reveal significantly negative associations between the dummy variables D_2 and D_3 (the sub-prime crisis in periods 3); hence, the finding of an inverse U-shaped curve gives rise to doubts at to whether unusual events, such as the sub-prime crisis, have any effect on spread, although the regressions have controlled the market trading effects on spread arising from the daily volume, volatility and price. We carry out a test for robustness by excluding the sub-prime contamination from our sample data, and present Figure 2 in an attempt to determine why the spread in the third period has a negative sign; the figure, which illustrates the average daily dollar quoted spread during our sample period, reveals an obvious inverse U-shaped curve between low latency and quoted spread during the full sample period.

<Figure 2 is inserted about here>

Following on from this, it appears that increased transparency has diverse effects on execution costs; hence, we surmise that the abnormal market situation is attributable to the sub-prime crisis and therefore continue to run the subsequent regressions aimed at isolating the contamination of the crisis. The regression models for the pre-sub-prime and post-sub-prime crisis periods are respectively expressed in Equations (2) and (3):

$$\begin{aligned} &Spread_t(QSpread_t, R\_QSpread_t, EffSpread_t, R\_Effspread_t) \\ &= \alpha_0 + \alpha_1 D_4 + \alpha_2 D_5 + \alpha_3 Volume_t + \alpha_4 HiLow_t + \alpha_5 \Pr ice_t + \varepsilon_t \end{aligned} \tag{2}$$

$$\begin{aligned} &Spread_t(QSpread_t, R\_QSpread_t, EffSpread_t, R\_Effspread_t) \\ &= \alpha_0 + \alpha_1 D_6 + \alpha_2 Volume_t + \alpha_3 HiLow_t + \alpha_4 \Pr ice_t + \varepsilon_t \end{aligned} \tag{3}$$

The results of these regressions are presented in Panel B of Table 4, where only *R_QSpread* are found to initially significantly rise, followed by a fall after a specific break point in the third period (according to the coefficient signs on the intercept, D_4 and D_5). However, *EffSpread* and *R_EffSpread* are consistently found to have negative associations with low latency. The regression results for the post-sub-prime crisis period are presented in Panel C of Table 4, which also shows a significantly negative relationship between all four spread and low latency. When removing the contamination of the financial crisis from our analysis, we find that the inverse U-shaped curve between low latency and *QSpread* (*R_EffSpread*) disappears and therefore conclude that the inverse U-shaped curve may be related to the sub-prime crisis period. Eventually, the market pre-trade transparency from persistent reductions in quote display refresh rate has a negative effect on spread.

Market depth

Sufficient market depth accommodates block orders, making it possible to conclude working order deals, whereas insufficient market depth is usually found to have a positive association with spread in the vacuum of orders offered. The TAIFEX provides depth information at the best bid/ask quote to the best five quotes; the best quote depth is therefore selected for our analysis in this study. Depth on the TAIFEX (the daily mean value of the sum of waiting orders at the best bid and ask quote prices) between 2005 and 2010 is illustrated in Figure 3, which clearly reveals a U-shaped curve.

<Figure 3 is inserted about here>

Similarly, we carry out our regressions on market depth as in Madhaven et al (2005) and Boehmer et al. (2005), building regression models for the full sample period, the pre-sub-prime crisis period and the post-sub-prime crisis period. The regression results on the impact of the different limit order book refresh intervals on depth at the best quotes are presented in Table 5, with Panel A showing that for the full sample period, the *DepthBid*, *DepthAsk* and *Depth* variables at the best quote reveal a U-shaped curve; hence, a reduction is found in the three depth variables at the best quote with low latency prior to a specific break point in the third period, whereas an increase is discernible after this point. However, by isolating the contamination of the sub-prime crisis period in Panels B and C of Table 5, we find a reduction in all three depth variables with low latency in the pre-sub-prime and post-sub-prime crisis period, because the U-shaped curve between low latency and depth variables in Panel A could interfere with the sub-prime crisis.

The results presented in Panel A of Table 5 indicate that relative depth, R_Depth_t (the imbalance between bid/ask market depth), appears to have a consistently positive relationship with low latency over all periods. According to our earlier results on the depth variables at the best quote, this indicates that with low latency, the smaller reduction in $DepthBid_t$ than in $DepthAsk_t$, leads to an increase in R_Depth_t prior to the specific break point in the third period, and that with low latency, the greater increase in $DepthBid_t$ than in $DepthAsk_t$ leads to an increase in R_Depth_t after the specific break point. And, there is the same phenomenon in the regressions without the contamination of the sub-prime crisis period.

<Table 5 is inserted about here>

Transient Volatility

Figure 4 illustrates the transient volatility of the TAIFEX (the daily mean value of the standard deviation in the mid-quote return during a fifteen-minute interval) between 2005 and 2010.

<Figure 4 is inserted about here>

In order to test intraday volatility, we adjust the Madhaven et al. (2005) regression models, as follows:

$$Volatility_{15,\tau}$$

$$= \alpha_0 + \alpha_1 D_1 + \alpha_2 D_2 + \alpha_3 D_3 + \alpha_4 N\_Trade_{15,t} + \alpha_5 HiLow_t + \alpha_6 \Pr ice_t + \varepsilon_t \quad (4)$$

$$Volatility_{15,\tau}$$

$$= \alpha_0 + \alpha_1 D_4 + \alpha_2 D_5 + \alpha_3 N\_Trade_{15,t} + \alpha_4 HiLow_t + \alpha_5 \Pr ice_t + \varepsilon_t \quad (5)$$

$$Volatility_{15,\tau}$$

$$= \alpha_0 + \alpha_1 D_6 + \alpha_2 N\_Trade_{15,t} + \alpha_3 HiLow_t + \alpha_4 \Pr ice_t + \varepsilon_t \quad (6)$$

Full sample period regression in left hand side of Table 6 reveals significantly negative coefficients on D_1 , D_2 and D_3, findings which imply the existence of a persistently negative relationship between low latency and intraday volatility. Besides, by isolating the contamination of the sub-prime crisis period in right hand side of Table 6, we still find a reduction in all three depth variables with low latency in the pre-sub-prime and post-sub-prime crisis period.

<Table 6 is inserted about here>

4.2 The around event sample analyses

According to the long term event study methodology, the investigation of such a long period likely suffers some biases from structure changes, because other events –primarily news events—may contaminate the results and be incapable to capture by market control variables or sub-prime crisis. Thus, we try to follow the approach of Boehmer et al. (2005), which study on a technological innovation in pre-trade transparency at the NYSE, focuses on short-term periods before and after the event. Accordingly, we choose 30 trading days for the length of each period.[6] We assume that our sample period is divided into three structures as structure A (Only using 60 trading days in each structure, 12 Jan 2006 ~ 17 Apr 2006), structure B (14 Dec 2008~18 Mar 2008), structure C (17 Jul 2009 ~ 9 Oct 2009), which d_B (d_C,) dummy variable could distinguish A from B (B from C) structures shown in Table 6. Firstly, we follow the method of Eom, Ok, and Park (2007) to test a standard event-study, without controlling for other structure variables, where DR_1 , DR_2 and DR_3 equals to unit as separately representing the "30-day" periods after the event of those three refresh rule change shown in Table 7. Secondly, we are interested in identifying the permanent effects of the change in the limit order book refresh interval for pre-trade transparency. For that purpose, we need to capture the additive effect of each rule change in which the market is in equilibrium with respect to traders' use of order flow information, one before the event and one after the event (such as A r_0 vs. A r_1, B r_1 vs. B r_2, C r_2 vs. C r_3), which dr_1 , dr_2 and dr_3 separately represent three refresh rule change shown in Table 7. We believe this choice strikes a balance between our desire to employ more data for the statistical tests on the one hand and both the stability of the estimates and the complexity of handling TAIFEX order-level data on the other.

<Table 7 is inserted about here>

Bid-ask spread

The t-test results in spread variables using a standard event study method are reported in Panel A of Table 8. The event-study method presumes that other things are the same in short-term 60 days sample period around each event. We find that the four spread variables (*Qspread*, *R_Qspread*, *EffSpread* and *R_EffSpread*) in post-event period are significantly lower than those in pre-event period for the three rule changes from r0 to r1, from r1 to r2 and from r2 to r3, which seems to indicate a decline in spread variables in each of public latency shortenings without controlling market environments.

<Table 8 is inserted about here>

Furthermore, we follow the method of Eom, Ok, and Park (2007) to test a standard event-study. The regression models are expressed in below Equations:

$$Spread_t(QSpread_t, R\_QSpread_t, EffSpread_t, R\_Effspread_t) \tag{7}$$

[6] We have also chosen 10, 60 and 90 days as the length of each period for empirical regression tests. Those results are also similar to ones of 30 days. We can provide those results by readers' request.

$$= \alpha_0 + \alpha_1 DR_1 + \alpha_2 Volume_t + \alpha_3 HiLow_t + \alpha_4 \Pr ice_t + \varepsilon_t$$

$$Spread_t(QSpread_t, R\_QSpread_t, EffSpread_t, R\_Effspread_t) = \alpha_0 + \alpha_1 DR_2 + \alpha_2 Volume_t + \alpha_3 HiLow_t + \alpha_4 \Pr ice_t + \varepsilon_t \quad (8)$$

$$Spread_t(QSpread_t, R\_QSpread_t, EffSpread_t, R\_Effspread_t) = \alpha_0 + \alpha_1 DR_3 + \alpha_2 Volume_t + \alpha_3 HiLow_t + \alpha_4 \Pr ice_t + \varepsilon_t \quad (9)$$

The results of these regressions are presented in Panel B of Table 9, where the coefficients of DR_1, DR_2 and DR_3 separately representing the three rule changes in the structure A, B and C are significantly negative in the dollar quoted spread, relative quoted spread, the effective and relative effective spreads regressions.

<Table 9 is inserted about here>

Most importantly, we surmise that the abnormal market situation might be attributable to the structure changes and run the subsequent regressions aimed at isolating the contamination of the structure change in long term sample period. The regression models are expressed in Equation (10):

$$Spread_t(QSpread_t, R\_QSpread_t, EffSpread_t, R\_Effspread_t) = \alpha_0 + \alpha_1 dr_1 + \alpha_2 d_B + \alpha_3 dr_2 + \alpha_4 d_C + \alpha_5 dr_3 + \alpha_6 Volume_t + \alpha_7 HiLow_t + \alpha_8 \Pr ice_t + \varepsilon_t \quad (10)$$

The results of these regressions controlling structure changes are presented in Panel A of Table 9, where all spread variables are consistently found to have negative associations with low latency under controlling structure changes from A to B and B to C, according to the negative coefficients of dr_1, dr_2 and dr_3 for three rule changes. Overall, we conclude that dramatically increased transparency of public latency should eventually lead to narrower spreads.

Market depth

The t-test results in Depth variables using a standard event study method are reported in Panel B of Table 8. The event-study method presumes that other things are the same in short-term 60 days sample period around each event. We find that the three Depth variables (*Depth*, *DepthBid* and *DepthAsk*) in post-event period are significantly higher than those in pre-event period for the three rule changes from r0 to r1, from r1 to r2 and from r2 to r3, which seems to indicate an increment in depth variables in each of public latency shortenings without controlling market environments.

Similarly, we run the regressions of short-term events aimed at isolating the contamination of the structure change. The results of these regressions are presented in Panel B of Table 10, where the coefficients of DR_1, DR_2 and DR_3 separately representing the three rule changes in the structure A, B and C are significantly positive in the *DepthBid*, *DepthAsk* and *Depth* variables regressions. Beside, we also run the regressions at isolating the contamination of the structure change. The results of these regressions are presented in Panel A of Table 10, where the *DepthBid*, *DepthAsk* and *Depth* variables at the best quote reveal a positive relationship with low public latency under controlling structure changes, according to the positive coefficients of dr_1, dr_2 and dr_3. Contrary to the results of full sample analyses in early section, our empirical results in short-term event without contamination of structure change show that a positive relationship is found to exist between low latency and market depth.

<Table 10 is inserted about here>

As regards market liquidity quality, Kumar, Sarin and Shastri (1998) suggest that lower spreads and higher depth together provide unambiguous evidence of higher liquidity. The negative relationship of low public latency and spread found in the present study is consistent with the finding of a positive relationship of low public latency and depth, which is also consistent with the conclusion of Kumar et al. (1998). Our empirical results for around event sample analyses show that market liquidity is positively associated with low public latency. The impact of increased transparency from low public latency is the positive effects, where dramatically increased transparency should lead to greater real-time information, implying more efficient prices and then narrower spreads because limit order submitters face a lower information asymmetry and a higher probability of trade execution. The substantially greater transparency enables the higher disclosure of private information stemming from more informed trades that would result in a lower adverse selection cost of subsequent limit order submitters and then decrease the spread. (Glosten, 1999; Baruch, 2005) Besides, the dramatically high speed trading from low public latency could bring a lower non-execution cost of limit order submitters and a narrower spread. Accordingly, both reduced costs of adverse selection and non-execution could motivate uninformed traders to submit more limit orders. We must observe a single kind of rule persistent changes to capture the evolution evidences of spread and liquidity in multiple levels of transparency, and then could provide the inferences of the positive effects of pre-trade transparency on depth and the negative effects on spread.

Transient volatility

The t-test results in transient volatility using a standard event study method are reported in Panel C of Table 8. We find that the transient volatility in post-event period is significantly lower than those in pre-event period for the three rule changes. For the regressions analyses of short-term events excluding the contamination of the structure change, the results in the right hang side of Table 11 show that the coefficients of DR_1, DR_2 and DR_3 separately representing the three rule changes in the structure A, B and C are significantly negative. We also run the regressions with controlling the structure changes, and the results of the regression in the left hand side of Table 11 reveal that all coefficients of dr_3 , dr_3 and dr_3 are significantly negative, indicating a persistently negative relationship between low latency and volatility. These results of short-term events, being consistent with the findings of Table 6 related to the full sample analyses, imply that the public low-latency would slightly decrease the transient volatility because increase in pre-trade transparency would lower the market uncertainty.

<Table 11 is inserted about here>

5. Conclusions

Exchanges prefer to reduce system latency and attract order flows in order to accelerate the overall process of order execution and information disclosure, thereby improving market quality. This is achieved by enabling investors to update quote prices more rapidly in response to incoming orders. Besides, algorithmic trading is now a major source of order flows; thus, milliseconds provide the competitive edge for marketplaces with regard to both the demand and provision of electronic execution services. Hence, exchanges are investing heavily in upgrading their systems with the ultimate aim of reducing the time required to send information to customers and to accept and handle their orders, thereby reducing transmission times to less than a millisecond; as a result, market participants are indirectly pressured into using such exchanges.

We investigate the effect of a specific technological innovation in pre-trade transparency (the increases in the quote display refresh rate) on measures of market quality. This is a nice way of testing whether a change related to the latency of all investors (public latency), and not just professional traders, has any real effects on the exchange. Changes in market design often have real-time impacts on transparency, which, in turn, leads to reactions amongst various market participants. Clearly, combined with the immediacy of the quote price, greater numbers of observations flashing across monitors provides traders with sufficient information to effectively manage their consumption and provision of liquidity. The evolution of liquidity from adjustments of market participants' strategies could substantially change the measures of market quality, such as spread, depth and transient volatility. So far, however, there has been no study in the academic literature on whether greater pre-trade transparency in the public latency of disclosing more information about limit orders in the book is beneficial. Our results provide empirical support, for the first time, for the view that improved pre-trade transparency of a limit-order book can be good for investors. The findings of the present study contribute to the extant literature by providing a better understanding of the ways in which disclosure speed in the electronic open limit book affects market quality.

As shown in the results of our empirical investigations, greater transparency gives rise to reactions amongst all market traders. According to the full sample analyses with excluding sub-prime contamination, our findings show that the increased market transparency from persistent reductions in quote display refresh rate has negatively associated with spread, depth and intraday volatility. Furthermore, since the investigation of a long term event-study methodology likely suffers some biases from structure changes which may contaminate the results and be incapable to capture by market control variables or sub-prime crisis, we provide the around event sample analyses to avoid the structure changes problem. According to the around event sample analyses, our findings show that the increased market transparency from persistent reductions in quote display refresh rate has negatively associated with spread and intraday volatility, and positively associated with depth. These empirical results support our expectation that low public latency should improve market quality. Besides, we can observe a single kind of rule persistent changes to capture the evolution evidences of spread and liquidity in multiple levels of pre-trade transparency, and then provide the empirical evidences as more insightful explanation for the nonlinearity.

In regulators attempts to attract foreign investors to their trading venues, global exchanges are engaged in ongoing competition to update their next-generation high-speed trading platforms, with the expectation of becoming more competitive than their counterparts. Huge amounts are being invested in developing trading platforms to compete with rival exchanges. We conclude that today's low-latency millisecond trading environment along with IT innovations have led to greater transparency and better market quality.

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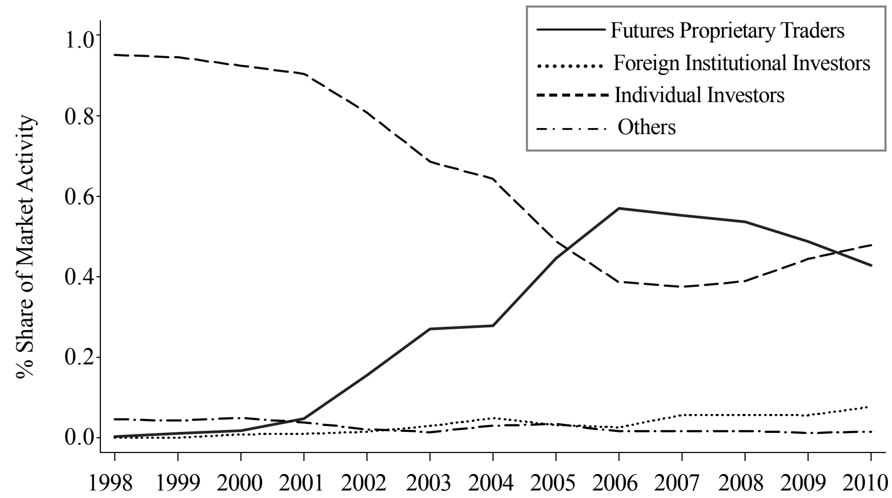

Figure 1 Percentage share of market activity amongst TAIFEX traders, 1998-2010

Note: Futures trading in the TAIFEX comprises of futures proprietary traders, foreign institutional investors, individual investors and others.

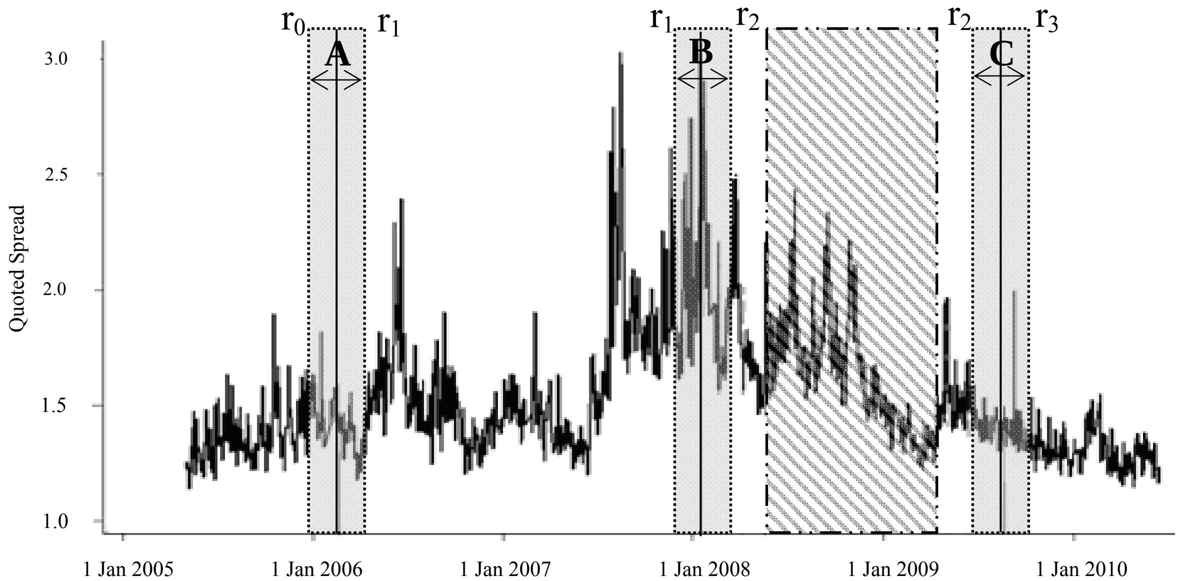

Figure 2 Quoted spread on the TAIFEX, 2005-2010

Note: The quoted spread is the daily mean value of the best bid minus the best ask. The vertical solid reference lines are set according to the different limit open book refresh intervals (periods 1 to 4). The zone featuring vertical dashed lines is defined as the sub-prime crisis period (1 July 2008 – 31 May 2009). Focusing on "30-day" periods before and after the events (r_0, r_1, r_2 and r_3), we assume that our sample period is divided into A, B and C structures.

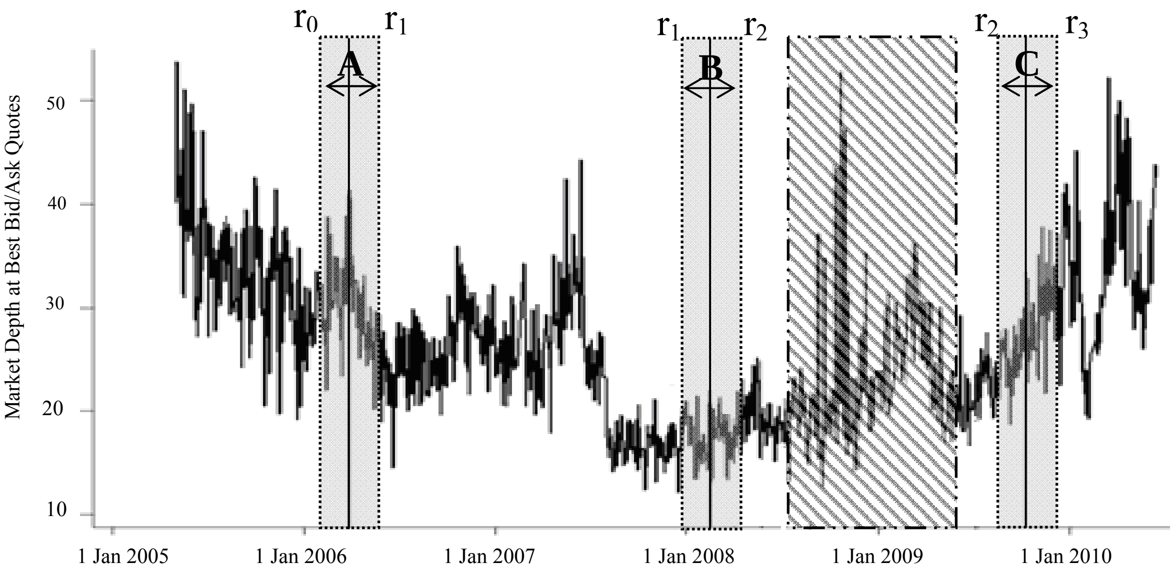

Figure 3 Market depth on the TAIFEX at the best bid/ask quotes, 2005-2010

Note: The market depth on the TAIFEX is the daily mean value of the sum of waiting limit orders at the best bid and ask quote prices. The vertical solid reference lines are set according to the different limit open book refresh intervals (periods 1 to 4). The zone featuring vertical dashed lines is defined as the sub-prime crisis period (1 July 2008 – 31 May 2009). Focusing on "30-day" periods before and after the events (r_0, r_1, r_2 and r_3), we assume that our sample period is divided into A, B and C structures.

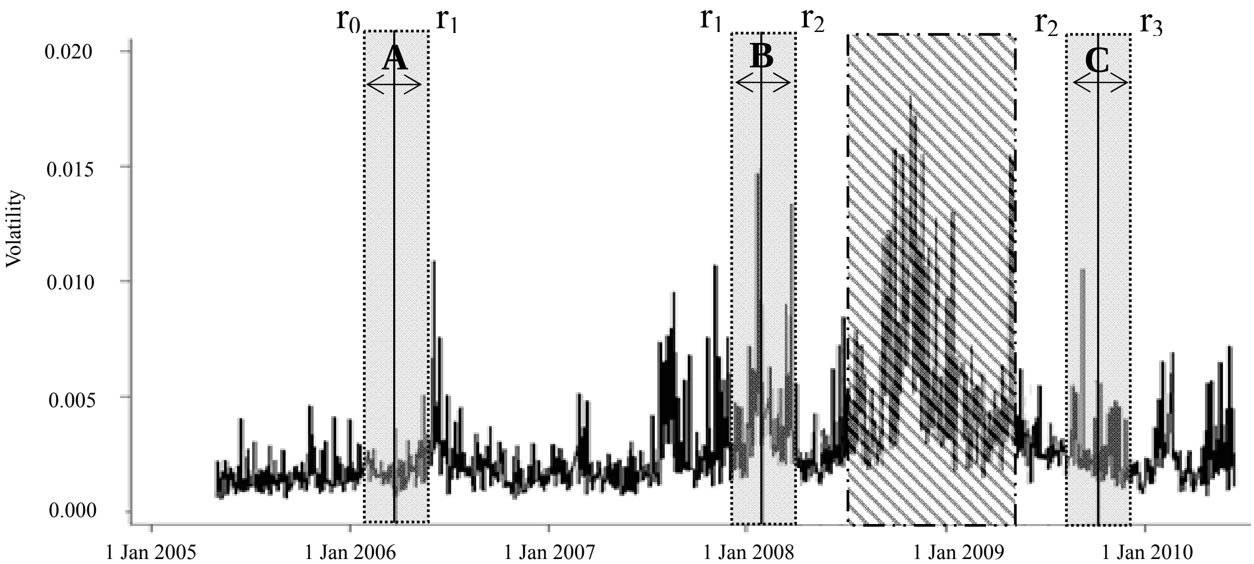

Figure 4 Volatility of fifteen-minute mid-quote returns on the TAIFEX, 2005-2010

Note: The 15-minute mid-quote return volatility on the TAIFEX is the daily mean value of the standard deviation of the mid-quote returns in a fifteen-minute interval. The vertical solid reference lines are set according to the different limit open book refresh intervals (periods 1 to 4). The zone featuring vertical dashed lines is defined as the sub-prime crisis period (1 July 2008 – 31 May 2009). Focusing on "30-day" periods before and after the events (r_0, r_1, r_2 and r_3), we assume that our sample period is divided into A, B and C structures.

Table 1 TAIFEX contract specifications

Item	Description
Underlying Index	Taiwan Stock Exchange Capitalization Weighted Stock Index (TAIEX)
Ticker Symbol	TX
Delivery Months	Spot month, the next calendar month, and the next three quarterly months
Last Trading Day	The third Wednesday of the delivery month of each contract
Trading Hours	08:45am to 1:45pm Taiwan time, Monday to Friday of all regular business days on the Taiwan Stock Exchange. 08:45am to 1:30pm on the last trading day for the delivery month contract.
Contract Size	NT$200 □ per index point
Minimum Price Fluctuation	One index point (NT$200)
Daily Price Limit	± 7% of the settlement price on the previous day

Table 2 Time windows and dummy variables of the full sample analyses

This table presents the dummy variables used in the regressions of hypotheses. The four different periods (different limit order book refresh intervals) correspond with the rule changes in full sample period. The whole sample is divided into the pre-sub-prime crisis and the post-sub-prime crisis based upon the occurrence of the sub-prime crisis (from 1 July 2008 to 31 May 2009) to set up the dummy variables.

	Limit Order Book Refresh Interval			
Time Window	Period 1 (5 seconds)	Period 2 (3 seconds)	Period 3 (1 second)	Period 4 (250 milliseconds)
Full Sample Period				
D_1, D_2, D_3	3 May 2005 - 3 Mar 2006	6 March 2006 –25 January 2008	28 January 2008 – 28 August 2009	31 August 2009 – 17 June 2010
	(0, 0, 0)	(1, 0, 0)	(1, 1, 0)	(1, 1, 1)
Pre-Sub-prime Crisis Period				
D_4, D_5	3 May 2005 - 3 Mar 2006	6 March 2006 –25 January 2008	28 January 2008 – 30 June 2008	–
	(0, 0)	(1, 0)	(1, 1)	–
Post-Sub-prime Crisis Period				
D_6	–	–	1 June 2009 – 28 August 2009	31 August 2009 – 17 June 2010
	–	–	(0)	(1)

Table 3 Summary statistics of TAIEX futures

This table reports the mean values and standard deviations of all of the market quality variables and controlling variables used in the examination of our hypotheses. The full sample period is divided into four sub-periods based upon the different limit order book refresh intervals, comprising of 5 seconds for period 1, 3 seconds for period 2, 1 second for period 3 and 0.25 seconds for period 4. Q_b (Q_a) is the best bid (ask) quote; *QSpread* is the quoted spread, which is equal to $Q_a - Q_b$; *R_QSpread* is the relative quoted spread which is equal to $100 \times$ *QSpread*/mid-quote; *EffSpread* is the effective spread, which is equal to $I \times 2 \times$ (transaction price −mid-quote) where I =1 when buyer initiated, and −1 when seller initiated; *R_EffSpread* is the relative effective spread, which is equal to $100 \times$ *EffSpread*/mid-quote; *Depth* is the sum of the waiting limit orders at the best bid and ask quote prices; *DepthBid* (*DepthAsk*) is the number of waiting limit orders at the best bid (ask) quote price; *R_Depth* is the relative depth of the best quote, which is equal to 100(*DepthBid* − *DepthAsk*)/*Depth*; *Volatility*$_{15}$ is the standard deviation of mid-quote returns during a fifteen minute interval; *N-Trade*$_{15}$ is the number of transactions during a fifteen minute interval; *Volume* is the total number of daily transactions; *HiLow* is the highest minus the lowest transaction daily prices; and *Price* is the daily closing price. The F-test reports the equal means of the four-periods. * indicates statistical significance at the 1% level.

Variables	Period 1		Period 2		Period 3		Period 4		*F*-value
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
Hypothesis 1: Spread									
QSpread	1.3995	0.7846	1.6915	1.1958	1.6074	1.0094	1.3199	0.7133	248984*
R_QSpread	0.0225	0.0126	0.0217	0.0152	0.0270	0.0181	0.0173	0.0095	762427*
EffSpread	1.3892	1.3841	1.6879	2.1843	1.6300	7.8242	1.2509	1.0757	19583*
R_EffSpread	0.0212	0.0143	0.0207	0.0180	0.0303	0.2383	0.0168	0.0142	349089*
Hypothesis 2: Depth									
Depth	33.4724	29.6111	23.6963	22.0893	21.8795	26.9957	31.0527	30.5968	155331*
DepthBid	16.5228	19.6670	11.7296	14.7419	11.1089	18.0634	15.6359	20.5578	293841*
DepthAsk	16.9497	21.7438	11.9668	15.8892	10.7707	19.3441	15.4168	21.3824	147109*
R_Depth	0.1904	56.9311	0.3040	55.7924	1.2020	55.3571	0.7357	56.8906	577.57*
Hypothesis 3: Volatility									
Volatility$_{15}$	0.0016	0.0007	0.0024	0.0017	0.0041	0.0028	0.0023	0.0013	1935.76*
N_Trade$_{15}$	1151.84	791.20	1799.46	1112.58	3552.60	1978.08	4295.74	2488.58	3952.92*
Control Variables									
Volume	25170.76	8359.91	39928.78	14577.49	79046.28	29330.02	92784.55	29839.35	9098968*
HiLow	76.3158	35.4273	134.7287	86.2185	161.1937	71.7663	125.4116	62.6173	1137658*
Price	6238.32	279.06	7842.75	960.92	6179.72	1409.95	7632.34	326.31	6143041*

Table 4 Regression results of the impact of the limit order book refresh interval on the bid-ask spread for full sample analyses

This table presents the regression results on the impact of the limit order book refresh interval on the dollar-quoted, relative-quoted, dollar-effective and relative-effective spreads for full sample analyses. The regression models for (i) the full sample period; (ii) the pre-subprime crisis period; and (iii) the post-subprime crisis period are as follows:

(i) $Spread_t\,(QSpread_t, R\_QSpread_t, EffSpread_t, R\_EffSpread_t) = \alpha_0 + \alpha_1 D_1 + \alpha_2 D_2 + \alpha_3 D_3 + \alpha_4 Volume_t + \alpha_5 HiLow_t + \alpha_6 Price_t + \varepsilon_t$

(ii) $Spread_t\,(QSpread_t, R\_QSpread_t, EffSpread_t, R\_EffSpread_t) = \alpha_0 + \alpha_1 D_4 + \alpha_2 D_5 + \alpha_3 Volume_t + \alpha_4 HiLow_t + \alpha_5 Price_t + \varepsilon_t$

(iii) $Spread_t\,(QSpread_t, R\_QSpread_t, EffSpread_t, R\_EffSpread_t) = \alpha_0 + \alpha_1 D_6 + \alpha_2 Volume_t + \alpha_3 HiLow_t + \alpha_4 Price_t + \varepsilon_t$

where *QSpread* is the quoted spread; *R_QSpread* is the relative quoted spread; *EffSpread* is the effective spread; *R_EffSpread* is the relative effective spread; $Volume_t$ is the total number of trades on day *t*; $HiLow_t$ is the highest transaction price minus the lowest transaction price on day *t*; and $Price_t$ is the closing price on day *t*. The dummy variables are as designated in Table 1. The regression results are presented in Panel A for the full sample, Panel B for the pre-sub-prime crisis period, and Panel C for the post-sub-prime crisis period. * indicates significance at the 1% level.

Variables	*QSpread*		*R_QSpread*		*EffSpread*		*R_EffSpread*	
	Coeff.	t-statistic	Coeff.	t-statistic	Coeff.	t-statistic	Coeff.	t-statistic
Panel A: Full Sample Period								
Intercept	-0.7293	-57.51*	0.2311	1192.93*	-1.8515	-49.2*	0.1740	110.79*
D_1	0.1140	141.31*	0.0028	222.82*	-0.0082	-3.35*	0.0003	2.99*
D_2	-0.0555	-93.55*	-0.0006	-61.62*	-0.1605	-90.42*	-0.0049	-66*
D_3	-0.2115	-387.39*	-0.0023	-273.56*	-0.1657	-103.25*	-0.0046	-68.47*
Volume	0.3835	784.97*	0.0059	787*	0.1740	120.42*	0.0052	86.32*
HiLow	-0.1259	-173.02*	-0.0025	-224.4*	0.1365	62.97*	0.0047	52.02*
Price	0.2048	194.03*	-0.0238	-1476.6*	0.0469	15.02*	-0.0254	-194.86*
F-statistic	295475*		295475*		14888.6*		22517*	
R^2	0.0492		0.0492		0.0028		0.0043	

Table 4 (*Contd.*)

Variables	*QSpread*		*R_QSpread*		*EffSpread*		*R_EffSpread*	
	Coeff.	t-statistic	Coeff.	t-statistic	Coeff.	t-statistic	Coeff.	t-statistic
Panel B: Pre-Sub-prime Crisis Period								
Intercept	-3.6570	-132.58*	0.1467	412.11*	-2.6583	-102.47*	0.1223	187.02*
D_4	0.0006	0.59	0.0003	23.81*	-0.0367	-35.74*	-0.0007	-25.78*
D_5	-0.0650	-74.62*	-0.0007	-61.67*	-0.1213	-148.52*	-0.0028	-137.93*
Volume	0.3653	380.55*	0.0047	375.62*	0.1745	191.87*	0.0045	194.41*
HiLow	0.1204	81.2*	0.0015	76.08*	0.1781	126.23*	0.0044	124.05*
Price	0.2609	87.36*	-0.0182	-471.61*	0.0903	32.21*	-0.0188	-265.83*
F-statistic	152274*		119973*		61198.9*		55526.1*	
R^2	0.0541		0.0431		0.0257		0.0234	
Panel C: Post-Sub-prime Crisis Period								
Intercept	6.9964	147.75*	0.2623	401.29*	1.8131	47*	0.2089	195.41*
D_6	-0.0184	-22.29*	-0.0004	-38.7*	-0.0526	-78.25*	-0.0017	-90.47*
Volume	0.1547	205.27*	0.0021	197.67*	0.0913	148.36*	0.0025	144.69*
HiLow	-0.0650	-51.54*	-0.0009	-54.35*	0.0130	12.56*	0.0003	9.87*
Price	-0.6315	-125.64*	-0.0272	-392.44*	-0.1921	-46.96*	-0.0230	-202.97*
F-statistic	47982.3*		198792*		34513.6*		97747.3*	
R^2	0.0163		0.0641		0.0125		0.0346	

Table 5 Regression results of the impact of the limit order book refresh interval on depth at the best quotes for full sample analyses

This table presents the regression results on the impact of the limit order book refresh interval on depth at the best bid and ask quote, depth at the best quotes, and relative depth of the best quotes for full sample analyses. The regression models for (i) the full sample period; (ii) the pre-subprime crisis period; and (iii) the post-subprime crisis period are as follows:

(i) $Depth\,(DepthBid_t, DepthAsk_t, Depth_t, R\_Depth_t) = \alpha_0 + \alpha_1 D_1 + \alpha_2 D_2 + \alpha_3 D_3 + \alpha_4 Volume_t + \alpha_5 HiLow_t + \alpha_6 Price_t + \varepsilon_t$

(ii) $Depth\,(DepthBid_t, DepthAsk_t, Depth_t, R\_Depth_t) = \alpha_0 + \alpha_1 D_4 + \alpha_2 D_5 + \alpha_3 Volume_t + \alpha_4 HiLow_t + \alpha_5 Price_t + \varepsilon_t$

(iii) $Depth\,(DepthBid_t, DepthAsk_t, Depth_t, R\_Depth_t) = \alpha_0 + \alpha_1 D_6 + \alpha_2 Volume_t + \alpha_3 HiLow_t + \alpha_4 Price_t + \varepsilon_t$

where $DepthBid_t$ ($DepthAsk_t$) is the depth at the best bid (ask) quote; $Depth_t$ is the depth at the best quotes; $R\_Depth_t = 100 \times (DepthBid_t - DepthAsk_t)/(DepthBid_t + DepthAsk_t)$; $Volume_t$ is the total number of trades on day t; $HiLow_t$ is the highest transaction price minus the lowest transaction price on day t; and $Price_t$ is the closing price on day t. The dummy variables are as designated in Table 1. The regression results are presented in Panel A for the full sample, Panel B for the pre-sub-prime crisis period, and Panel C for the post-sub-prime crisis period. * indicates significance at the 1% level.

Variables	*DepthBid*		*DepthAsk*		*Depth*		*R_Depth*	
	Coeff.	t-statistic	Coeff.	t-statistic	Coeff.	t-statistic	Coeff.	t-statistic
Panel A: Full Sample Period								
Intercept	51.4444	214.52*	46.0384	180.33*	97.4828	272.78*	23.0002	30.92*
D_1	-3.0243	-198.25*	-3.3199	-204.42*	-6.3442	-279.07*	0.6671	14.1*
D_2	-1.6505	-147.23*	-1.8898	-158.35*	-3.5403	-211.92*	0.6991	20.1*
D_3	4.5333	439.06*	4.4694	406.6*	9.0027	585.11*	0.1601	5*
Volume	-2.8755	-311.25*	-2.8833	-293.15*	-5.7587	-418.29*	0.3212	11.21
HiLow	1.1769	85.53*	1.0018	68.39*	2.1788	106.26*	-0.5679	-13.3*
Price	-3.9781	-199.29*	-3.1021	-145.97*	-7.0802	-238.02*	-2.1025	-33.95*
F-statistic	109987*		99518.4*		199809*		492.92*	
R^2	0.0189		0.0171		0.0338		0.0001	

Table 5 (*Contd.*)

Variables	*DepthBid*		*DepthAsk*		*Depth*		*R_Depth*	
	Coeff.	t-statistic	Coeff.	t-statistic	Coeff.	t-statistic	Coeff.	t-statistic
Panel B: Pre-Sub-prime Crisis Period								
Intercept	51.4444	214.52*	46.0384	180.33*	97.4828	272.78*	23.0002	30.92*
D_4	-3.0243	-198.25*	-3.3199	-204.42*	-6.3442	-279.07*	0.6671	14.1*
D_5	-1.6505	-147.23*	-1.8898	-158.35*	-3.5403	-211.92*	0.6991	20.1*
Volume	4.5333	439.06*	4.4694	406.6*	9.0027	585.11*	0.1601	5*
HiLow	-2.8755	-311.25*	-2.8833	-293.15*	-5.7587	-418.29*	0.3212	11.21
Price	1.1769	85.53*	1.0018	68.39*	2.1788	106.26*	-0.5679	-13.3*
F-statistic	76094.2*		78507.4*		151231*		123.22*	
R^2	0.0278		0.0287		0.0538		0.0001	
Panel C: Post-Sub-prime Crisis Period								
Intercept	67.7728	175.13*	69.0433	166.4*	136.8162	238.66*	21.6662	15.4*
D_6	-2.8192	-185.49*	-2.8547	-175.18*	-5.6739	-252.01*	0.5220	9.45*
Volume	-1.8347	-150.09*	-2.2431	-171.15*	-4.0778	-225.19*	0.8575	19.3*
HiLow	-3.2097	-238.36*	-3.6871	-255.39*	-6.8968	-345.76*	0.7771	15.88*
Price	2.9974	144.11*	3.3106	148.46*	6.3080	204.73*	-0.9158	-12.11*
F-statistic	55471*		51960*		101509*		189.36*	
R^2	0.0187		0.0176		0.0338		0.0001	

Table 6 Regression results of the impacts of the limit order book refresh interval on transient volatility for full sample analyses

This table presents the regression results of the impact of the limit order book refresh interval on transient volatility and price levels for full sample analyses. The regression models for short-term volatility, considering the interaction with the frequency of trades, are as shown below for (i) the full sample period; (ii) the pre-sub-prime crisis period; and (iii) the post-sub-prime crisis period:

(i) $Volatility_{15,\tau} = \alpha_0 + \alpha_1 D_1 + \alpha_2 D_2 + \alpha_3 D_3 + \alpha_4 N\_Trade_{15,\tau} + \alpha_5 HiLow_t + \alpha_6 Price_t + \varepsilon_t$

(ii) $Volatility_{15,\tau} = \alpha_0 + \alpha_1 D_4 + \alpha_2 D_5 + \alpha_3 N\_Trade_{15,\tau} + \alpha_4 HiLow_t + \alpha_5 Price_t + \varepsilon_t$

(iii) $Volatility_{15,\tau} = \alpha_0 + \alpha_1 D_6 + \alpha_2 N\_Trade_{15,\tau} + \alpha_3 HiLow_t + \alpha_4 Price_t + \varepsilon_t$

where $Volatility_{15,\tau}$ is the standard deviation in returns for the quote mid-point during a fifteen minute interval; $N\_Trade_{15,\tau}$ is the number of transactions calculated once every fifteen minutes; $HiLow_t$ is the highest transaction price minus the lowest transaction price on day t; and $Price_t$ is the closing price on day t.

Variables	Full Sample Period		Pre-Subprime Crisis Period		Post-Subprime Crisis Period	
	Coeff.	t-statistic	Coeff.	t-statistic	Coeff.	t-statistic
Intercept	0.0079	30.47*	0.0044	11.93*	0.0273	17.33*
D_1	-0.0004	-22.24*	–	–	–	–
D_2	-0.0012	-52.04*	–	–	–	–
D_3	-0.0017	-78.68*	–	–	–	–
D_4	–	–	-0.0003	-16.44*	–	–
D_5	–	–	-0.0008	-35.04*	–	–
D_6	–	–	–	–	-0.0011	-25.12*
$N\_Trade_{15,\tau}$	0.0009	79.34*	0.0006	55.11*	0.0007	32.1*
HiLow	0.0006	66.97*	0.0006	68.97*	0.0004	24.66*
price	-0.0019	-71.3*	-0.0013	-29.22*	-0.004	-23.44*
F-statistic	7296.82*		3173.25*		1542.41*	
R^2	0.6531		0.5263		0.5569	

Table 7 Time windows and dummy variables of the sample data for around event sample analyses

This table presents the dummy variables used in the regressions of hypotheses for around event sample analyses. Our sample period is partially divided into three structures as structure A, B and C, which d_B (d_C,) dummy variable could distinguish A from B (B from C). The length of each structure is 60 trading days, which is divided into 30 days in the pre- and post-event period.

Time Window	Limit Order Book Refresh Interval					
	Period 1 (5 seconds)	Period 2 (3 seconds)		Period 3 (1 second)		Period 4 (250 milliseconds)
Structure Change						
	~ A Structure, r_0	A Structure, r_1 ~	B Structure, r_1	B Structure, r_2 ~	C Structure, r_2	C Structure, r_3 ~
	12 Jan 2006- 3 Mar 2006	6 Mar 2006- 17 Apr 2006	–	–	–	–
	(0,0,0,0,0)	(1,0,0,0,0)	–	–	–	–
dr_1 , d_B, dr_2 , d_C, dr_3	–	–	14 Dec 2007- 25 Jan 2008	28 Jan 2008- 18 Mar 2008	–	–
	–	–	(1,1,0,0,0)	(1,1,1,0,0)	–	–
	–	–	–	–	17 Jul 2009- 28 Aug 2009	31 Aug 2009- 9 Oct 2009
	–	–	–	–	(1,1,1,1,0)	(1,1,1,1,1)
DR_1, DR_2, DR_3	DR_1=0	DR_1=1	DR_2=0	DR_2=1	DR_3=0	DR_3=1

Table 8 T-test results in market quality using a standard event study method for around event sample analyses

This table shows the results of the t-test in spread, depth and transient volatility using a standard event study method for the three changes of regulation. The market quality measures are as follows: Q_b (Q_a) is the best bid (ask) quote; *QSpread* is the quoted spread, which is equal to $Q_a - Q_b$; *R_QSpread* is the relative quoted spread which is equal to $100 \times$ *QSpread*/mid-quote; *EffSpread* is the effective spread, which is equal to $I \times 2 \times$ (transaction price −mid-quote) where I =1 when buyer initiated, and −1 when seller initiated; *R_EffSpread* is the relative effective spread, which is equal to 100□*EffSpread*/mid-quote; *Depth* is the sum of the waiting limit orders at the best bid and ask quote prices; *DepthBid* (*DepthAsk*) is the number of waiting limit orders at the best bid (ask) quote price; *R_Depth* is the relative depth of the best quote, which is equal to 100□(*DepthBid* − *DepthAsk*)/*Depth*; $Volatility_{15}$ is the standard deviation of mid-quote returns during a fifteen minute interval. Our sample period is partially divided into three structures as structure A, B and C, and the rule change from r0 to r1 (from r1 to r2; from r2 to r3) happened to structure A (B; C). The length of each structure is 60 trading days, which is divided into 30 days in the pre- and post-event period. * indicates significance at the 1% level.

Variables	$A_{(r0,r1)}$				$B_{(r1,r2)}$				$C_{(r2,r3)}$			
	Mean		Diff	t-statistic	Mean		Diff	t-statistic	Mean		Diff	t-statistic
	Before	After	(After-Before)		Before	After	(After-Before)		Before	After	(After-Before)	
Panel A: Spread												
QSpread	1.4474	1.3656	-0.0819	-49.49*	2.2396	1.8739	-0.3656	-160.63*	1.4030	1.3975	-0.0054	-4.87*
R_QSpread	0.0220	0.0208	-0.0012	-45.98*	0.0280	0.0234	-0.0046	-160.26*	0.0205	0.0191	-0.0014	-89.93*
EffSpread	1.4731	1.3061	-0.1670	-46.71*	2.3453	1.7607	-0.5846	-182.94*	1.3982	1.3294	-0.0688	-34.97*
R_EffSpread	0.0223	0.0199	-0.0025	-45.33*	0.0293	0.0220	-0.0074	-183.2*	0.0204	0.0182	-0.0023	-83.93*
Panel B: Depth												
Depth	30.1122	33.0277	2.9203	50.23*	16.9379	17.3594	0.4215	13.86*	23.8123	25.5929	1.7806	66.24*
DepthBidt	15.1603	15.9116	0.7513	19.85*	8.5083	8.7313	0.2230	10.48*	12.1032	12.8824	0.7792	41.2*
DepthAskt	14.9749	17.1338	2.1690	49.64*	8.4243	8.6282	0.2038	9.5*	11.7091	12.7104	1.0014	53.6*
R_Deptht	0.7982	-0.5919	-1.3900	-11.24*	0.4682	0.9609	0.4927	5.77*	1.4500	0.4624	-0.9877	-14.63*
Panel C: Volatility												
$Volatility_{15,\tau}$	0.0016	0.0014	-0.0002	-2.07*	0.0035	0.0030	-0.0006	-3.64*	0.0019	0.0021	0.0002	2.19*

Table 9 Regression results of the impact of the limit order book refresh interval on the bid-ask spread for around event sample analyses

This table presents the regression results on the impact of the limit order book refresh interval on spreads. The regression models under controlling structure changes are as follows:

(i) $Spread_t\,(QSpread_t, R\_QSpread_t, EffSpread_t, R\_EffSpread_t) = \alpha_0 + \alpha_1 d_1 + \alpha_2 d_2 + \alpha_3 d_3 + \alpha_4 d_4 + \alpha_5 d_5 + \alpha_6 Volume_t + \alpha_7 HiLow_t + \alpha_8 Price_t + \varepsilon_t$

(ii) $Spread_t\,(QSpread_t, R\_QSpread_t, EffSpread_t, R\_EffSpread_t) = \alpha_0 + \alpha_1 DR_1 + \alpha_2\, Volume_t + \alpha_3 HiLow_t + \alpha_4 Price_t + \varepsilon_t$

(iii) $Spread_t\,(QSpread_t, R\_QSpread_t, EffSpread_t, R\_EffSpread_t) = \alpha_0 + \alpha_1 DR_2 + \alpha_2\, Volume_t + \alpha_3 HiLow_t + \alpha_4 Price_t + \varepsilon_t,$

(iv) $Spread_t\,(QSpread_t, R\_QSpread_t, EffSpread_t, R\_EffSpread_t) = \alpha_0 + \alpha_1 DR_1 + \alpha_2\, Volume_t + \alpha_3 HiLow_t + \alpha_4 Price_t + \varepsilon_t$

where *QSpread* is the quoted spread; *R_QSpread* is the relative quoted spread; *EffSpread* is the effective spread; *R_EffSpread* is the relative effective spread; $Volume_t$ is the total number of trades on day t; $HiLow_t$ is the highest transaction price minus the lowest transaction price on day t; and $Price_t$ is the closing price on day t. The dummy variables are as designated in Table 3. * indicates significance at the 1% level.

Panel A: Regressions controlling structure changes

Variables	*QSpread*		*R_QSpread*		*EffSpread*		*R_EffSpread*	
	coeff.	t-statistic	coeff.	t-statistic	coeff.	t-statistic	coeff.	t-statistic
Intercept	15.8619	109.67*	0.3994	208.54*	11.5773	49.7*	0.3387	107.71*
dr_1	-0.0278	-12.03*	-0.0005	-16.61*	-0.1209	-31.83*	-0.0019	-36.83*
d_B	0.9610	234.59*	0.0126	232.86*	0.9276	140.56*	0.0121	135.92*
dr_2	-0.3276	-188.06*	-0.0040	-173.48*	-0.5055	-179.35*	-0.0062	-163.21*
d_C	-0.6167	-185.44*	-0.0083	-189.18*	-0.5932	-110.97*	-0.0080	-110.4*
dr_3	-0.1088	-66.19*	-0.0016	-71.64*	-0.0307	-11.77*	-0.0004	-12.74*
Volume	0.2606	145.53*	0.0034	142.48*	0.2713	93.92*	0.0036	92.22*
HiLow	-0.0740	-24.46*	-0.0010	-23.75*	0.1672	33.69*	0.0022	32.33*
Price	-1.6840	-106.49*	-0.0435	-207.81*	-1.4870	-58.58*	-0.0404	-117.89*
F-statistic	65681.7*		40016.2*		34712.2*		23272.1*	
R^2	0.0934		0.0591		0.056		0.0382	

Table 9 (*Contd.*)

Panel B: Regression for a single regulation change

	QSpread						*R_QSpread*					
Regulation Change	$A_{(r0,r1)}$		$B_{(r1,r2)}$		$C_{(r2,r3.)}$		$A_{(r0,r1)}$		$B_{(r1,r2)}$		$C_{(r2,r3.)}$	
Variables	coeff.	t-statistic	coeff.	t-statistic	coeff.	t-statistic	coeff.	t-statistic	coeff.	t-statistic	coeff.	t-statistic
Intercept	-1.766	-5.11*	22.9528	87.85*	0.8704	3.17*	0.1466	27.94*	0.504	153.83*	0.1936	51.44*
DR_1	-0.0523	-28.72*	–	–	–	–	-0.0007	-26.87*	–	–	–	–
DR_2	–	–	-0.2839	-112.31*	–	–	–	–	-0.0035	-109.72*	–	–
DR_3	–	–	–	–	-0.0008	-2.37*	–	–	–	–	-0.0001	-2.39*
Volume	-0.0762	-16.63*	-0.0229	-3.91*	-0.0154	-2.69*	-0.0013	-17.94*	-0.0001	-0.94	-0.0003	-3.24*
HiLow	0.121	38.69*	0.3881	97.07*	0.1992	70.36*	0.0019	39.61*	0.0048	95.03*	0.0026	68.05*
Price	0.3946	10.05*	-2.5087	-88.6*	-0.03	-1.07	-0.0137	-22.9*	-0.0557	-156.94*	-0.0207	-54.12*
F-statistic	1121.5*		13503.9*		4325.82*		990.05*		18282.5*		7352.79*	
R^2	0.0052		0.0347		0.0063		0.0046		0.0465		0.0106	

	EffSpread						*R_EffSpread*					
Regulation Change	$A_{(r0,r1)}$		$B_{(r1,r2)}$		$C_{(r2,r3.)}$		$A_{(r0,r1)}$		$B_{(r1,r2)}$		$C_{(r2,r3.)}$	
Variables	coeff.	t-statistic	coeff.	t-statistic	coeff.	t-statistic	coeff.	t-statistic	coeff.	t-statistic	coeff.	t-statistic
Intercept	-0.2955	-0.39	21.5878	58.46*	-11.3452	-23.38*	0.1623	14.25*	0.4865	105.04*	0.0153	2.3
DR_1	-0.1385	-35.08*	–	–	–	–	-0.0021	-34.42*	–	–	–	–
DR_2	–	–	-0.4706	-131.34*	–	–	–	–	-0.0058	-129.61*	–	–
DR_3	–	–	–	–	-0.1317	-34.44*	–	–	–	–	-0.0018	-35.03*
Volume	0.0096	0.95	0.3627	42.72*	0.1712	16.86*	0.0001	0.56	0.0047	44.4*	0.0024	17.6*
HiLow	0.1383	20.24*	0.2915	51.2*	0.2979	59.65*	0.0021	20.58*	0.0036	50.19*	0.0039	57.47*
Price	0.1191	1.39	-2.7654	-69.21*	1.0555	21.4*	-0.0171	-13.24*	-0.0589	-117.47*	-0.0048	-7.06*
F-statistic	750.16*		12964.3*		5430.89*		711.76*		15603.2*		6985.74*	
R^2	0.0041		0.0371		0.0083		0.0039		0.0444		0.0106	

Table 10 Regression results of the impact of the limit order book refresh interval on depth at the best quotes for around event sample analyses

This table presents the regression results on the impact of the limit order book refresh interval on depth at the best bid and ask quote, depth at the best quotes, and relative depth of the best quotes. The regression models under controlling structure change are as follows:

(i) $Depth\ (DepthBid_t, DepthAsk_t, Depth_t, R\_Depth_t) = \alpha_0 + \alpha_1 dr_1 + \alpha_2 d_B + \alpha_3 dr_2 + \alpha_4 d_C + \alpha_5 dr_3 + \alpha_6 Volume_t + \alpha_7 HiLow_t + \alpha_8 Price_t + \varepsilon_t$

(ii) $Depth\ (DepthBid_t, DepthAsk_t, Depth_t, R\_Depth_t) = \alpha_0 + \alpha_1 DR_1 + \alpha_2 Volume_\tau + \alpha_3 HiLow_t + \alpha_4 Price_t + \varepsilon_t$

(iii) $Depth\ (DepthBid_t, DepthAsk_t, Depth_t, R\_Depth_t) = \alpha_0 + \alpha_1 DR_2 + \alpha_2\ Volume_\tau + \alpha_3 HiLow_t + \alpha_4 Price_t + \varepsilon_t$,

(iv) $Depth\ (DepthBid_t, DepthAsk_t, Depth_t, R\_Depth_t) = \alpha_0 + \alpha_1 DR_1 + \alpha_2\ Volume_\tau + \alpha_3 HiLow_t + \alpha_4 Price_t + \varepsilon_t$

where $DepthBid_t$ ($DepthAsk_t$) is the depth at the best bid (ask) quote; $Depth_t$ is the depth at the best quotes; $R\_Depth_t = 100 \times (DepthBid_t - DepthAsk_t)/(DepthBid_t + DepthAsk_t)$; $Volume_t$ is the total number of trades on day *t*; $HiLow_t$ is the highest transaction price minus the lowest transaction price on day *t*; and $Price_t$ is the closing price on day *t*. The dummy variables are as designated in Table 3. * indicates significance at the 1% level.

Panel A: Regressions controlling structure changes

Variables	*DepthBidt*		*DepthAskt*		*Depth*		*R_Deptht*	
	coeff.	t-statistic	coeff.	t-statistic	coeff.	t-statistic	coeff.	t-statistic
Intercept	-158.9031	-52.15*	-53.5286	-25.32*	-105.3745	-48.78*	160.5351	20.78*
dr_1	2.1882	44.91*	0.3493	10.33*	1.8389	53.23*	-1.4255	-11.54*
d_B	-18.7000	-216.68*	-7.9915	-133.47*	-10.7086	-175.03*	5.1013	23.31*
dr_2	0.1277	3.48*	0.0389	2.53*	0.0888	3.41*	0.2970	3.19*
d_C	6.8829	98.24*	3.0531	62.81*	3.8298	77.11*	-1.7749	-9.99*
dr_3	0.5064	14.62*	0.3435	14.29*	0.1629	6.63*	0.1489	1.7
Volume	-3.0437	-80.67*	-1.6391	-62.61*	-1.4047	-52.51*	-0.1032	-1.08*
HiLow	3.6549	57.37*	1.9229	43.51*	1.7320	38.35*	-0.8470	-5.24*
Price	18.6991	56.13*	6.3547	27.49*	12.3444	52.27*	-17.1042	-20.25*
F-statistic	16110.4*		18272.1*		33574.9*		123.39*	
R^2	0.0246		0.0279		0.05		0.0002	

Table 10 (*Contd.*)

Panel B: Regression for a single regulation change

Depth						
Regulation Change	$A_{(r0,r1)}$		$B_{(r1,r2)}$		$C_{(r2,r3.)}$	
Variables	coeff.	t-statistic	coeff.	t-statistic	coeff.	t-statistic
Intercept	213.6004	23.4*	-134.1492	-59.56*	-123.7755	-26.85*
DR_1	1.9001	39.48*	–	–	–	–
DR_2	–	–	0.025	2.15*	–	–
DR_3	–	–	–	–	0.0497	2.37*
Volume	4.2648	35.26*	0.5833	11.52*	1.7744	18.48*
HiLow	-0.2267	-2.75*	-1.0643	-30.88*	-1.7204	-36.16*
Price	-27.5524	-26.56*	15.7765	64.64*	13.9869	29.8*
F-statistic	2040.84*		2181.62*		2470.74*	
R^2	0.0095		0.0058		0.0036	

DepthBidt						
Regulation Change	$A_{(r0,r1)}$		$B_{(r1,r2)}$		$C_{(r2,r3.)}$	
Variables	coeff.	t-statistic	coeff.	t-statistic	coeff.	t-statistic
Intercept	396.8782	32.74*	-230.1467	-70.72*	-126.576	-19.09*
DR_1	2.2209	34.75*	–	–	–	–
DR_2	–	–	0.1191	3.78*	–	–
DR_3	–	–	–	–	0.7158	13.67*
Volume	9.3756	58.38*	1.2263	16.77*	2.8774	20.84*
HiLow	-1.1029	-10.06*	-1.8652	-37.45*	-3.6039	-52.67*
Price	-52.3191	-37.99*	27.0868	76.8*	15.2832	22.64*
F-statistic	978.21*		757.15*		1257.45*	
R^2	0.0046		0.002		0.0018	

DepthAskt						
Regulation Change	$A_{(r0,r1)}$		$B_{(r1,r2)}$		$C_{(r2,r3.)}$	
Variables	coeff.	t-statistic	coeff.	t-statistic	coeff.	t-statistic
Intercept	183.2778	23.2*	-97.0477	-41.62*	-2.8005	-0.6
DR_1	0.3208	7.7*	–	–	–	–
DR_2	–	–	0.101	4.48*	–	–
DR_3	–	–	–	–	0.6661	18.08*
Volume	5.1108	48.83*	0.6581	12.56*	1.1031	11.35*
HiLow	-0.8763	-12.26*	-0.8	-22.41*	-1.8835	-39.11*
Price	-24.7667	-27.59*	11.4074	45.14*	1.2963	2.73*
F-statistic	1207.44*		1541.24*		1405.57*	
R^2	0.0056		0.0041		0.002	

R_Deptht						
Regulation Change	$A_{(r0,r1)}$		$B_{(r1,r2)}$		$C_{(r2,r3.)}$	
Variables	coeff.	t-statistic	coeff.	t-statistic	coeff.	t-statistic
Intercept	138.7851	5.36*	147.9888	15.08*	167.5351	10.05*
DR_1	-1.598	-11.71*	–	–	–	–
DR_2	–	–	0.4522	4.76*	–	–
DR_3	–	–	–	–	0.2257	1.92*
Volume	-0.4947	-1.44	-1.4235	-6.45*	-0.13	-0.37
HiLow	-0.881	-3.76*	0.7402	4.93*	-0.603	-3.51*
Price	-14.6542	-4.98*	-15.092	-14.19*	-18.3031	-10.79*
F-statistic	52.81*		69.88*		96.31*	
R^2	0.0002		0.0002		0.0001	

Table 11 Regression results of the impacts of the limit order book refresh interval on volatility and price levels for around event sample analyses

This table presents the regression results of the impact of the limit order book refresh interval on short-term volatility and price levels. The regression models for short-term volatility, considering the interaction with the frequency of trades, are as shown below for

(i) $Volatility_{15,\tau} = \alpha_0 + \alpha_1 dr_1 + \alpha_2 d_B + \alpha_3 dr_2 + \alpha_4 d_C + \alpha_5 dr_{3,\tau} + \alpha_6 N\_Trade_{15,\tau} + \alpha_7 HiLow_t + \alpha_8 Price_t + \varepsilon_t$,

(ii) $Volatility_{15,\tau} = \alpha_0 + \alpha_1 DR_2 + \alpha_2 N\_Trade_{15,\tau} + \alpha_3 HiLow_t + \alpha_4 Price_t + \varepsilon_t$

(iii) $Volatility_{15,\tau} = \alpha_0 + \alpha_1 DR_3 + \alpha_2 N\_Trade_{15,\tau} + \alpha_3 HiLow_t + \alpha_4 Price_t + \varepsilon_t$,

(iv) $Volatility_{15,\tau} = \alpha_0 + \alpha_1 DR_1 + \alpha_2 N\_Trade_{15,\tau} + \alpha_3 HiLow_t + \alpha_4 Price_t + \varepsilon_t$

where $Volatility_{15,\tau}$ is the standard deviation in returns for the quote mid-point during a fifteen minute interval; $N\_Trade_{15,\tau}$ is the number of transactions calculated once every fifteen minutes; $HiLow_t$ is the highest transaction price minus the lowest transaction price on day t; and $Price_t$ is the closing price on day t.

	$Volatility_{15,\tau}$							
	Regression controlling structure changes		*Regression for a single regulation change*					
Variables			$A_{(r0,r1)}$		$B_{(r1,r2)}$		$C_{(r2,r3)}$	
	Coeff.	t-statistic	Coeff.	t-statistic	Coeff.	t-statistic	Coeff.	t-statistic
Intercept	0.0195	7.97*	-0.0133	-3. 8*	0.0293	6.92*	-0.0002	-0.04
dr_1	-0.0002	-8.32*	–	–	–	–	–	–
d_B	0.0015	22.22*	–	–	–	–	–	–
dr_2	-0.0005	-17.61*	–	–	–	–	–	–
d_C	-0.0014	-25.12*	–	–	–	–	–	–
dr_3	-0.0001	-1.73	–	–	–	–	–	–
DR_1	–	–	-0.0002	-13.78*	–	–	–	–
DR_2	–	–	–	–	-0.0005	-12.6*	–	–
DR_3	–	–	–	–	–	–	-0.0002	-4.33*
$N\_Trade_{15,\tau}$	0.0014	38.67*	0.0009	27.33*	0.0015	19.71*	0.0012	17*
HiLow	0.0003	14.14*	0.0006	1.36	-0.005	-10.83*	-0.0015	-2.2
price	-0.0038	-13.97*	0.0001	3.16*	0.0006	10.76*	0.0003	8.12*
F-statistic	896.34*		241.26*		345.43*		196.27*	
R^2	0.6888		0.4665		0.5758		17.76	