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Central Bank Interventions and Limit Order Behavior in the Foreign Exchange Market

Masayuki Susai
Nagasaki University

Yushi Yoshida
Faculty of Economics
Kyushu Sangyo University

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Masayuki Susai* Yushi Yoshida**
Nagasaki University Kyushu Sangyo University

Abstract:
We investigate the intra-day effect of interventions in both the post- global crisis and pre-crisis periods by the Bank of Japan (BOJ) in foreign exchange markets using limit order data at intra-day high frequency. First, we find that the relationship between order flow and market return in dollar/yen exchange markets breaks down following unexpected and very high volumes of offer/sell orders by BOJ interventions. Then, a simple methodology of using large recursive residual is proposed to detect the exact timing of interventions. Second, the dataset allows measuring how long an individual limit order stays in the market. With the measured lifetime of limit orders, we find interventions, detected by the proposed methodology, significantly reduce the life-time of limit order in the market. By applying the same methodology on non-intervention days, we find no such evidence on the life-time of limit orders although large recursive residuals are also pervasive in non-intervention days.

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Keywords: the Bank of Japan; Central bank interventions; Foreign exchange market; Life time of limit order; Order flow.

*****Masayuki Susai, msusai@nagasaki-u.ac.jp. 1-14, Bunkyo-machi, Nagasaki, 852-8521 Japan. Susuai acknowledges financial support from JSPS KAKENHI Grant Number 22330097.
******Yushi Yoshida (corresponding author), yushi@ip.kyusan-u.ac.jp. 2-3-1 Matsukadai, Higashiku, Fukuoka, 813-8503 Japan. Yoshida acknowledges financial support from the Zengin Foundation for Studies on Economics and Finance and JSPS KAKENHI Grant Number 23530308. We thank Kentaro Iwatubo, Yoshihiro Kitamura, Eiichi Miyagawa, Kimiko Sugimoto and other participants at Kobe University and Rissho University for their useful comments.

1. Introduction

The foreign exchange market interventions by the Bank of Japan (BOJ) were both voluminous and frequent in 2003 and 2004. US dollars equivalent to 20,246.5 (2003) and 14,831.3 (2004) billion Japanese yen, were purchased on the yen/dollar exchange market over 82 (2003) and 47 (2004) trading days. However, after the last day of the BOJ intervention on March 16, 2004, the Ministry of Finance of Japan and the BOJ quietly observed the movements of the Japanese yen on foreign exchange markets despite the fact that the Japanese yen was experiencing its historically highest level of appreciation since the World War II.

At the beginning of 2007, the sub-prime housing market in the U.S. started plummeting, and the consequent financial turmoil spread to the rest of the world. The US dollar and Euro depreciated against the other major currencies, especially against the Japanese yen. After six years of inactivity, the BOJ intervened in the yen/dollar exchange market on September 15, 2010, to the surprise of many market participants[1]. The size of the intervention transaction per day was unprecedentedly high, at 2,124.9 billion yen[2]. This is equivalent of 25,601 (24,999) million US dollars, calculated at the rate of 83.0 (85.0) Japanese yen per US dollar.

In this paper, we investigate the effects of the BOJ intervention on September 15, 2010 on trading activities on the yen/dollar market of the Electronic Broking System (EBS). To determine whether the findings are specific to this event, i.e., the first time in six years and the first time after the global crisis, we also apply the same methodology to five intervention days during the pre-crisis period. The major two contributions of this investigation are the following: First, we find that the relationship between order flow and market return in dollar/yen exchange markets breaks down following unexpected and very high volumes of offer/sell orders by BOJ interventions. Then, a simple methodology of using large recursive residual is proposed to detect the exact

[1] Prior to September 15, 2010, Mr. Noda, then Minister of Finance, repeatedly spoke to the media saying that the MOF and the BOJ would take necessary actions, including interventions, to halt further appreciation of the Japanese yen against the US dollar. However, the market participants, as reported frequently in the media, did not believe that the MOF and the BOJ would intervene in the yen-dollar exchange market on this particular day. Mr. Noda revealed in a morning interview with the press on the same day that the MOF requested the intervention of the BOJ at 10:30 AM (1:30 in GMT).

[2] After this intervention, the BOJ intervened in the foreign exchange market to the amount of 692.5 billion Japanese yen on March 18, 2011 and (the historically highest amount per day) 4,512.9 billion Japanese yen on August 4, 2011. By the end of November, 2011, the Ministry of Finance reports that the total value of interventions between October 28 and November 28, 2011 was 9,916 billion Japanese yen.

timing of interventions. Second, the dataset allows measuring how long an individual limit order stays in the market. With the measured lifetime of limit orders, we find interventions, detected by the proposed methodology, significantly reduce the life-time of limit order in the market. We find interventions significantly reduce the life-time of limit order by about 27 to 44 seconds. By applying the same methodology on non-intervention days, we find no such evidence on the life-time of limit orders although large recursive residuals are also pervasive in non-intervention days.

The remainder of this paper is structured as follows. The next section discusses the key concepts used in this paper and reviews the relevant studies in the literature. Section 3 describes the structure of the EBS dataset. Section 4 summarizes distinctive characteristics of the yen/dollar foreign exchange market on the day that the BOJ intervened for the first time in six years and reports preliminary investigations of the EBS dataset. Section 5 provides the empirical results on the relationship between order flows and exchange rate returns and proposes the simple method of detecting the exact timing of interventions (and after-effects) by using recursive errors. Section 6 investigates the impact of intra-day interventions on limit order behavior of foreign exchange market participants. By limit order behavior in this paper, we focus on the life-time (how long an individual limit order stays in the market) of limit orders. Section 7 provides robustness checks on the effect of interventions on the life-time of limit orders by applying the same method on non-intervention days. The final section discusses the findings and reports the conclusions.

2. Order flow, limit order, and intervention

In this section, we discuss the existing literature, with an emphasis on the relationship between three important features of this study: the use of limit orders as order flows, measuring the lifetime of limit orders, and an investigation of intervention at intra-day frequency. First, we argue that further investigation of the possible information dissemination role of limit orders is necessary. The current definition of order flow is based on actual transactions, i.e., observationally equivalent to market orders[3]. Second, the investigation of limit orders requires a new approach because, unlike market orders, most limit orders are canceled (or revised with a new price). We propose to investigate the effect of possible determinants of the life (i.e., the length of time that they remain in the order book) of limit orders. Third, using intra-day high frequency data for limit orders on the foreign exchange market, detection of the exact

[3] Market orders are orders matching the existing best quote in the market, and limit orders are orders set at specific prices, which may not be the same as the best quotes.

timing of intervention becomes an unavoidable issue[4]. Using an unusual, isolated incident of a publicized timing of intervention by the BOJ, we test the accuracy of an intervention-timing candidate found using a proposed approach and intend to apply the same approach to other interventions if the approach is proven valid. In the following, we discuss the three key concepts used in this paper in turn: the relationship of order flow to market and limit orders, the life-time of limit orders, and interventions at intra-day frequency.

2-1. The relationship of order flow to market and limit orders

The microstructural approach to the foreign exchange market (e.g., Lyons, 1997) emphasizes the role of order flow as a determinant of the exchange rate. Order flow is defined as the net result of buyers' initiated transactions minus sellers' initiated transactions (Evans and Lyons, 2002b). Because customer transactions are private dealer information, order flow in interbank transactions disseminates this information and affects the market price. Acquiring proprietary order flow data from one of the largest market makers, Cerrato et al. (2011) and Marsh (2011) investigate the effect of order flows of various customer types on exchange rate. Order flow is found to affect exchange rate by reflecting macroeconomic information (Rime et al., 2010 and Frömmel et al. 2011) and commodity price (King et al., 2010). In this context, market orders are treated as the only tool conveying private information throughout the market, whereas the role of limit orders is considered to be only passive, at best providing liquidity to the market.

However, current foreign exchange markets, which are dominated by electronic brokering platforms such as EBS and Reuters, are limit order markets. Cumulative limit orders constitute the order book with best bid-ask quotes, and submitted market orders are matched with existing limit orders at the best quotes. The number of limit orders submitted exceeds that of market orders in various financial markets. The theoretical framework in which limit order traders act only as liquidity providers is not suitable for explaining the current limit order markets.

Theoretical models have been developed to allow a trader to choose between market and limit orders, e.g., Cohen et al. (1981), Foucault (1999) and Bloomfield et al. (2005), among others. Unlike market orders, limit orders face the risk of non-execution.

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[4] See Menkhoff (2010) for a current survey on the high-frequency analysis of interventions and Vitale (2011) for a theoretical model of interventions in a market microstructure model.

Foucault (1999) examines the sub-game perfect equilibrium in a dynamic limit order market in which a trader chooses to submit either a market or limit order, with explicit consideration for non-execution risk and the risk of being picked off (or free-option risk). The results show that high volatility leads to more limit orders than market orders being placed and to a lower fill rate, i.e., the probability of being hit by a market order, for a limit order. Considering the two types of traders in a model, Bloomfield et al. (2005) show that informed traders and liquidity traders use both market and limit orders. Informed traders, in particular, use market orders to realize profit at the opening of the market and switch to limit orders as the market price approaches true value at the close of the market.

Based on theoretical developments regarding limit orders, we argue that the limit order has a more active role in disseminating private information to the market than market orders[5]. In this paper, therefore, we define order flow as the bid limit orders minus the offer limit orders. We investigate whether the order flow defined by limit orders has a significant effect on the market price on the foreign exchange market.

2-2. Life-time of limit orders

Limit orders by their nature need not be executed instantly and are frequently canceled without any transaction taking place. Many studies document high levels of cancellations in various limit order markets. Biais et al. (1995) is the first to investigate the order book of the limit order market at the Paris Bourse, which provides traders with the best five quotes and the corresponding volumes each time a new order or cancellation occurs. They document that approximately 20 percent of orders (at best five quotes) are canceled[6]. Harris and Hasbrouck (1996) document that 56.2 percent of limit orders on the New York Stock Exchange remain unfilled. This figure should not be interpreted as active cancellation, as some limit orders simply remain unmatched at the close of the market. Using the complete tick data for a company on the Stockholm Stock Exchange, Hollifield and Miller (2004) report that the execution probability for two

[5] The effects of limit orders on market characteristics are also investigated empirically and theoretically. As an empirical work, Biais et al. (1995) find that the conditional probability of placing limit orders rather than market orders is larger when the bid-ask spread is large or the order book is thin. In the model of Foucault et al. (2007), in which limit order traders possess asymmetric information about future volatility, the bid-ask spread signals the size of future volatility.

[6] This percentage is calculated by the ratio between unconditional new orders and cancellations shown in Table III (p. 1670, Biais et al., 1995).

days is 68, 33, and 12 percent for limit orders that are, respectively, 1, 2, and 3 ticks away from the best quote. Eventually, 88 percent of limit orders with prices 3 ticks away from the best quote are canceled. Yeo (2005) reports that the ratio of cancellations to submitted limit orders on the New York Stock Exchange has recently increased to 40 percent[7]. Hasbrouck and Saar (2002) document that roughly 25 (40) percent of limit orders are canceled after two (ten) seconds on the Island ECN, which constitutes 11 % of the trades on the Nasdaq exchange in 1999.

This large number of canceled limit orders can be attributed to the order splitting strategy and undercutting, according to Yeo (2005). Traders split orders in multiple submissions when they intend not to disseminate their private information. This strategy results in multiple cancellations when traders revise their orders. On the other hand, traders who compete to undercut other traders need to revise their prices frequently. The dynamic limit order market model of Foucault (1999) indicates that higher volatility leads to a lower fill rate. A lower fill rate, then, can be interpreted as a higher probability of cancellation in the foreign exchange market because no specific closing time exists. Foucault et al. (2005) theoretically show that the average time to a transaction increases with the size of the spread. This result in turn can be interpreted as indicating a lower fill rate at a fixed time interval during sporadic incoming orders.

To investigate why a significant proportion of order activities consists of cancelations and revisions, Fong and Liu (2010) consider the effect of non-execution risk, free-option risk, and monitoring cost in the order strategy. They find that both a closer submitted price to the best bid-ask quotes and a larger order volume increase the likelihood of cancellation or order revision. Using probit analysis, Yeo (2005) finds that a move in the market quote away from the submitted price induces cancellations. Both a larger volume in limit order and a larger volume at the best quote, i.e., the depth at quotes, deter cancellations.

Susai and Yoshida (2012) investigates the determinants of life-time of limit orders in the JPY/USD foreign exchange market. They measure how long each limit order stays in the market by calculating the length of time between the time stamp of order submission and that of either cancelation or transaction execution. The full discussions on how the possible determinants, conditional on market conditions and other participants behaviors, may influence the limit order behaviors in foreign

[7] Yeo (2005) compares the percentage of cancellations in all submitted requests, which include market orders, limit orders, and cancelations. Note that this percentage has the highest limit of 50 percent for cancellations because the number of cancellations cannot exceed the number of limit orders. Approximately 20 percent of orders were cancellations in 2001, compared with 5 percent in 1990.

exchange market.

2-3. Intervention at intra-day frequency

The availability of intervention data at intra-day level for the Swiss National Bank (hereafter SNB) motivates the research by Fischer and Zurlinden (1999), Payne and Vitale (2003), and Pasquariello (2007), among other studies. Using tick by tick data directly, Fischer and Zurlinden (1999) find that intervention, especially the first transaction, affects the exchange rate movement. Payne and Vitale (2003) also examine the SNB interventions by aggregating tick data at 15-minute intervals, whereas Fischer and Zurlinden (1999) used irregularly spaced tick series. They find that the SNB intervention has a stronger impact when it is leaning with the wind and concerted with other central banks. Pasquariello (2007) further aggregates tick by tick data into daily variables.

Chari (2007) combines the news reports of interventions with tick by tick quotes from Reuters and finds that the BOJ and the FRB interventions lead to increased volatility and a widening of bid-ask spreads. Using hourly aggregates of tick data for the Czech krouna-euro, Scalia (2008) finds that interventions (news) by the Czech National Bank increase the impact of order flow on the exchange rate. In contrast, by aggregating tick data for the Russian rouble-US dollar into 30-second intervals, Melvin et al. (2009) find that the price impact of order flow is smaller on intervention days.

The exact timing of interventions can be traced back to headline news reports (e.g., Chari, 2007); however, the inaccuracy of news reports regarding interventions is well documented in Klein (1993), Osterberg and Wetmore Humes (1993), and Fischer (2006). Among the central banks making their daily intervention data available to the public, only the SNB reveals to her counterpart that transactions are carried out for the purpose of intervention, see Fischer (2006) for detail. The exact time in minutes can be confirmed only for SNB interventions. Regarding the interventions of other central banks, researchers may make educated guesses about the exact timing of particular intervention episode by gathering newswire reports and scrutinizing the tick data but are never able to confirm whether their guesses are correct. Notwithstanding this vagueness about the timing of interventions, on a single occasion (September 15, 2010), the Minister of Finance publicly revealed the exact timing of a BOJ intervention, see footnote 1. This incident provides a great advantage to BOJ intervention research, and we use this fact to its full extent to check the validity of our proposed methodology to detect the timing of interventions.

3. The EBS data structure

Traders can either initiate a quote (i.e., submit a limit order) or match a posted quote (i.e., submit a market order). In the EBS dataset, all data entries are assigned one of five indicators: QS, QD, HS, HAD, and DSM. A quote begins with QS and a specific 20-digit ID and ends with QD. A hit begins with HS and ends with HAD. When two parties are matched in a transaction, DSM records the information for the transaction. The life of a quote can be described by the four cases shown in Figure 1: (1) a quote is deleted by cancellation; (2) a quote is filled either by another quote or by a market order; (3) a quote is canceled after part of the order is executed; (4) a quote is filled by multiple transactions. In the EBS dataset, which we purchased with a limited contract, all data cannot be made public unless aggregated to conceal the characteristics of individual transactions[8].

4. Summary of trading activities on September 15, 2010

The dataset is all limit orders in the EBS JPY/USD spot market with the sample covering the period between 21:00:00 (GMT) on September 14, 2010 and 20:59:59 (GMT) on September 15, 2010. The number of all limit orders is 625,725. A large portion of orders is submitted literally within a split second after the last order has been placed in the market. The orders submitted within a second after the last order constitutes 97.3 percent (608,793) of all orders for the day. In addition, approximately 0.7 percent of all orders are submitted simultaneously, measured in terms of milliseconds, with another order. This extremely fast speed of orders is explained in part by the pervasive use of algorithm trading using computers[9]. The asymmetric information models described in Easley and O'Hara (1987, 1992) suggest that large orders and short durations are evidence of trading by informed traders. Manganelli (2005) find supporting evidence for the link between short durations and trading by informed traders on the NYSE.

4-1. Order volume and rate by minute intervals

In the sample period of 24 hours, the number of limit orders is 625,725, time-stamped in milliseconds. Due to the irregular time spans of quote submissions, interpreting a series of raw data requires special care, even for a simple graph. We

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8 For a more detailed description of this EBS dataset, see Susai and Yoshida (2012).

9 Corwin and Lipson (2011) distinguish program (algorithm) traders, institutional traders, retail traders, and member traders in their empirical analysis of NYSE-listed securities. See Section 2 of their paper for the significant presence of program traders.

choose to convert these raw quote data to minute intervals. The minute interval sums all volumes for limit orders submitted within one minute. For example, the volume for 23:02 covers all transactions processed between 23:02:00 and 23:02:59. The minute interval rate is the rate for the earliest limit order in the next minute. If no limit order is submitted in the current minute, the previous minute interval rate is maintained.

Figure 2 provides the simultaneous limit order volume and JPY/USD rate. The beginning of swift intervention by the BOJ near 1:00 (GMT) is obvious in the figure, although a smaller BOJ intervention before this time cannot be ruled out. Limit order volume for the 01:32 minute interval increased suddenly to 4,235 million US dollars from 167 million US dollars in the previous minute interval. In approximately ten minutes, the JPY/USD rate increased from 82.915 (mid-rate) at 01:31 (minute interval) to 83.835 (mid-rate) at 01:40 (minute interval). The Japanese yen continued depreciating and remained at approximately 85.70 at the end of the day.

4-2. Hourly order size by order type

The order size in the dataset ranges from a minimum of one million US dollars to a maximum of 430 million US dollars (Figure 3). The size of orders used most is the minimum requirement of one million US dollars, and the use generally declines with increasing size of orders except for some focal numbers such as 10 million. The clustering in small orders is consistent with the limit of open positions for traders (Cheung and Chinn, 2001). The intraday position limit of most dealers in the US does not exceed 50 million US dollars. Cheung and Chinn (2001) report in their survey that 54 % (74 %) of dealers are authorized to have a maximum open position of less than 25 (over 50) million US dollars. Orders exceeding 50 million US dollars are exceptionally high against the limit of open positions for the most trading institutions. For the intervention days in the pre-crisis period, the maximum volumes of limit orders are 100, 520, 500, 500, and 300 million US dollars, respectively, for September 12, 2003; September 30, 2003; December 10, 2003; January 9, 2004; and March 5, 2004.

Based on the limit data reported in Figure 2, there is substantial variation in the activity of the foreign exchange market, especially on the intervention day. In this subsection, we break down the market orders by hour and compare the characteristics of orders between limit and market orders and between offer (sell) and bid (buy) orders. Table 1 reports the number of orders submitted in a particular one-hour period. Consistent with the transaction volume reported in Figure 2, panel (A) in Table 1 indicates that the number of orders exceeds 47,000, i.e., there were approximately 13 orders per second after 01:00, and the trading continues to be highly active until 15:00.

In terms of dollar purchase interventions by the BOJ, the frequency of order type does not hint at any peculiarity possibly caused by the official intervention.

Panel (B) in Table 1 provides the hourly breakdown of order size on the foreign exchange market. The average size of orders varies from 1.14 million US dollars at 17:00 to 2.09 million US dollars at 21:00. It is noteworthy that the average volume of 1:00 (the start of the sharp depreciation of the Japanese yen) takes place within the high part of the range at 1.49 million US dollars. The maximum volumes per orders are 430, 411, and 300 million US dollars, respectively at 12:00, 8:00, and 1:00.

We further investigate order activity by examining the hourly breakdown of order size by market order types in Panel (C) in Table 1, which provides the number of orders greater than or equal to 10 and 50 million US dollars for bid, offer, and both. Focusing on the three most active orders in each category, the orders at 1:00, 2:00, and 7:00 show quote activities that are active in high-volume orders. In these high-volume order categories, the number of bids exceeding offers is observed at more hours.

5. Empirical analysis by using aggregate data at minute intervals

In this section we investigate the relationship between order flows and exchange rate returns by using aggregated data at minute intervals. Our choice of aggregating at minute intervals is the best compromise between taking advantages of data availability at the tick level and the aggregate concept of order flows by definition. The next subsection provides on the estimation results on the relationship between order flows and exchange rate returns and the following subsections discuss the method to detect the exact timing (and possible after-effects) of intra-day interventions.

5-1. Exchange rate return and order flow

The effect of order flow on price change is well documented (Jones et al., 1994, Evans and Lyons, 2002). In the literature, the net order flow is the difference between purchase orders and sales orders. Distinguishing intervention days from non-intervention days, Marsh (2011) estimates the effect of net order flow on the change in the exchange rate. Interestingly, the significant effect of order flow on non-intervention days disappears on intervention days.

The net order flow is constructed for minute intervals between 21:00 on September 14, 2010 and 20:59 on September 15, 2010. As discussed in detail in Section 2, we define the net quote order flow as the bid limit order (dollar purchase) minus the offer limit order (dollar sales), and a positive value indicates a net purchase order for dollars. Figure 4 shows the net order flows of yen/dollar spot foreign exchange market on the EBS by minute. The US dollar purchase order by the BOJ intended to depreciate the Japanese yen should appear as a positive value in the figure.

Plotting the net order flow against the change in exchange rate in Figure 5, we observe a positive relationship between the net dollar purchase and a positive return of the yen/dollar exchange rate. More formally, following the simple regression approach in Marsh (2011), we estimate the following equation (1):

$$R_t = \alpha_0 + \alpha_1 OF_t + \varepsilon_t, \qquad (1)$$

where R_t is the change in the log of the exchange rate at minute intervals (used in Figure 2), OF_t is the net order flow by minute and error terms, ε_t, are independent and normally distributed with means zero and variance, σ^2.

The upper panel of Table 2 reports the estimation results for September 15, 2010. The coefficient of net order flow is correctly signed and statistically significant at the one-percent level. The fitness of regression in terms of adjusted R^2 is 0.31 and is relatively high compared to the order flow literature. It is noteworthy that order flow in previous studies is defined using market orders (or observationally equivalent transactions).

We also estimated equation (1) for the five intervention days in the pre-crisis period. The estimation results are shown in the lower panel of Table 2. The coefficients of order flow are all statistically significant at the five-percent level, but the degrees of fitness of the regression are smaller than that for the post-crisis priod. In this study, we obtain supporting evidence that the limit order version of order flow also affects the price. This result supports the notion that the submission of a limit order carries important private information to be disseminated through the market.

5-2. Stability of the relationship between order flow and exchange rate

Now, reflecting the fact that previous studies using daily exchange rate data and daily order flow data can distinguish intervention days from non-intervention days as in Marsh (2011), we test whether the parameters of the empirical model in equation (1) is stable throughout the entire period including pre-intervention hours, intervening hours, and post-intervention hours. For this examination, we implement the CUSUM test for the residual from the regression of equation (1). The cumulated sum of the residuals is plotted along the 95 percent upper-bound and lower-bound lines in Figure 6. The structural change is first detected at the 95 percent level at 02:03 on September 15, 2010. It is noteworthy that the cumulated sum of the residuals begins a sharp increase near 01:30. We have evidence that the relationship between the order flow and exchange rate returns is affected by the BOJ interventions.

The cumulated sums of the residuals are similarly plotted for five intervention days in the pre-crisis period in Figure 7. Strikingly, the standard CUSUM tests do not reject the null hypothesis of no structural change occurring during the pre-crisis period except for September 30, 2003 in Panel B of Figure 7. On September 30, 2003, the cumulative sum of the residuals exceeds the 95 percent upper bound at 23:25 (GMT).

What is striking in these plots of the cumulative sum of residuals and the cumulative sum of squared residuals is that sudden increases are observed, almost vertical increases, at several points in the sample. Three occur on September 15, 2010, one on September 12, 2003, three on September 30, 2003, two on December 10, a less obvious one on January 9, 2004, and at least two on March 5, 2004. These plots indicate that unusually high volume orders by the BOJ interventions can be detected at the minute or at least hour level by plotting the cumulative sum of the residuals. This reflects the fact that the relationship between limit order flow and exchange rate drastically changes when the BOJ is intervening in the foreign exchange market.

5-3. **intra-day intervention detection**

Given the strong detection power of recursive residuals for intervention activities, we formally introduce our proposed method in this subsection. Let x_t be (*1*, *OF*$_t$), $X'_{t-1} = [x_1, ..., x_{t-1}]$, y_t be R_t and $Y'_{t-1} = [y_1, ..., y_{t-1}]$. Let a'_t be the least-squares estimates of $[\alpha_0, \alpha_1]$ based on the first t observations. Under the hypothesis of constant parameters and constant variance of error terms, recursive residual, w_t, is proved to follow $N(0, \sigma^2)$, see Brown et al. (1975).

$$w_t = \frac{y_t - x'_{t-1} a_{t-1}}{\sqrt{1 + x'_t (X'_{t-1} X_{t-1})^{-1} x_t}} \qquad (2)$$

By using the estimated standard deviation determined by $\hat{\sigma}^2 = S_T / (T-2)$ where S_T is the residual sum of squares after fitting the model to the entire observations, $w_t / \hat{\sigma}^2$ is asymptotically normal with zero mean and unity variance.

Instead of using pre-specified statistical significance level, we choose the threshold levels which vary from 0.5 to 4.0 by 0.5 steps. With these threshold values, we define binary intervention variable, $INTERV_t$, which takes the value of one when recursive residual exceeds the corresponding threshold values and zero otherwise. For an illustrative purpose, we report that the number of observations exceeding the threshold value of 4 is 14 out of 1436 observations, in September 15, 2010. In terms of percentage, this 1 percent (14/1436) exceeds far beyond the level of 0.02 percent for the standard normal distribution at four standard deviations. Note that these extreme values may originate from the well know fact that error terms in financial assets follow non-normal distribution, especially with fat tails. We see in the following sections that these extreme values are whether mere statistical outliers or meaningful indicators of intra-day interventions.

6. The effect of intra-day interventions on limit order behavior

In this section we investigate whether intervention variables, constructed in a manner of section 5-3, have significant effect on the financial behaviors of participants in the JPY/USD foreign exchange market. First, we introduce the life-time estimation model, closely following Susai and Yoshida (2012), and apply the model to six intervention days in subsection 6-1. Then we add *INTERV* variables in the life-time estimation model to see whether the BOJ intervention activities (or just extreme values of recursive residuals) may affect the life-time of limit orders in subsection 6-2.

6-1. Life-time estimation model

For each limit order *i*, clock times are measured at the start of order, $t^s(i)$, and at the end of order, $t^e(i)$. The volume and quote are recorded as v_i and q_i. The best bid and ask (offer) are time-varying and are $b(t)$ and $o(t)$, respectively. I_i is an indicator function, taking the value of one for bid orders and zero for offer orders. The order book is kept as the sum of the volume at the rate by each tick, by 0.01 yen, on the bid and offer sides, $bv(t, rate)$ and $ov(t, rate)$, respectively.

$$d_i^{se} = \beta_1 Vol_i + \beta_2 Gap_i + \beta_3 Depth_i + \beta_4 Calm_i + \varepsilon_{t^s(i)} \qquad (3)$$

where $d_i^{se} = t^e(i) - t^s(i)$, $d_i^{ss} = t^s(i) - t^s(i-1)$, and ε_t is independently and identically distributed. Four independent variables are defined as follows: $Vol_i = v_i$,

$Gap_i \equiv I_i \left| b(t^s(i)) - q_i \right| + (1 - I_i) \left| o(t^s(i)) - q_i \right|$,

$Depth_i \equiv \sum_{j=b_i-0.04}^{b_i} bv(t^s(i), j) + \sum_{j=o_i}^{o_i+0.04} ov(t^s(i), j)$, and

$$Calm_i \equiv \sum_{j=i-19}^{i} d_j^{ss} .$$

The estimation results for equation (3) are shown in Table 4. The lifetimes of all limit orders are calculated, except for the first 29 instances due to the reconstruction of the order book to recover the best bid and ask quotes. The lifetime of these limit orders are regressed on four independent variables. All estimated coefficients are statistically significant at the one percent level. First, larger individual order volumes affect the order lifetime positively. As discussed in Section 4-2 and shown in Figure 4, most limit orders are submitted at a minimum size of one million US dollars. The estimated coefficient indicates, when other effects are controlled for, that minimum volume orders leave the order book within ten seconds (9.898 seconds) on average. Second, the larger the difference between the quote and market prices, the longer a limit order stays in the order book. If a quote price is 0.01 points away from the market price, the additional lifetime of a limit order is approximately 26 seconds. Third, market depth hastens the exit of a limit order from the market. The more orders are stocked in the order book, the more rapidly a limit order disappears from the market. Note that an infinitesimal increase, i.e., 1 million US dollars, in the order book does not have a large effect. An additional 100 million US dollars shortens the lifetime of limit orders by approximately 18 seconds. Fourth, the calmness (the reciprocal of volatility) of the market allows a limit order to stay longer in the order book. At the mean value of the Calm variable (2.15 from Table 3), a limit order stays approximately 11 seconds in the order book on average.

The estimation may be biased if both hit orders and canceled orders are included in the same sample because the former is more likely to represent orders with quotes close to a contemporaneous market price and thus has a shorter life time. We also investigate the empirical model of equation (3) using only canceled limit orders, and the results are shown in the third and fourth columns of Table 4. The qualitative results are very similar to those of the sample including all limit orders.

To shed light on the empirical question of whether the global financial crisis affects the behaviors of foreign exchange market, we repeat the same exercise for the five different days on which the BOJ interventions took place. We note that both the changes in the overall market behavior due the global financial crisis and the different effects of long-forgotten interventions may cause different response patterns in the estimation results between samples recorded during the pre- and post-crisis periods. In Table 5, the qualitative results of the sample recorded before the crisis in terms of the degree of fitness of the regressions, statistical significance, and the signs of the coefficients are quite consistent with those of the sample after the crisis, except for the positive coefficient of $Depth_i$ on Apr 9, 2004.

By comparing the range of the estimated coefficients in the pre-crisis period with those in the post-crisis period, we find that the coefficients of Gap and Calm in the post-crisis period fall outside of those in the pre-crisis period. For Vol, the estimated coefficients range from 4 to 31 in the pre-crisis period, and 9.898 (all orders) and 13.316 (canceled orders) in the post-crisis period lie within the range. For Depth, the estimated coefficients range from -0.7 to 0.14, and -0.182 (all) and -0.217 (canceled) also lie within the range.

However, for Gap, the effect of quote prices deviating from the market price on the life of limit orders is approximately half of the minimum value of the range in the pre-crisis period. This implies that limit orders on Sep 15, 2010 were withdrawn from the order book much faster than during the pre-crisis period. No-execution risk and foregone opportunity cost are much higher in the market after the crisis.

Comparison of the estimated coefficients of Calm shows that a slower-paced market condition during the post-crisis period allows limit orders to enjoy positions in the order book for longer periods. In other words, the relative exiting decision time from the order book is shorter in the market during a volatile period than a calm period after the crisis.

6-2. The effect of intra-day interventions on life-time

Given the significant change in the magnitude of recursive residuals plotted as cumulated sum of residuals in Figure 6 at the same timing as the announced official intervention by the BOJ on September 15, 2010, we propose to construct an intervention proxy variable at minute intervals. This (intermediate) intervention variable takes the value of one when a recursive residual from the regression in equation (1) exceeds the threshold value and zero otherwise. We only account for large positive errors in this study because all interventions are US dollar purchase, but for a general case of interventions in both directions recursive residuals in absolute terms should be applied. The threshold values are chosen to at least cover the obvious intervention timing of around 1:30 (GMT) and not include too much portion of the entire sample. These values are 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0. By this way, each minute interval is assigned to either one or zero. The number (the percentage) of minutes assigned the value of one is 260 minutes (18.1%), 134 (9.3%), 85 (5.9%), 49 (3.4%), 32 (2.2%), and 23 (1.6%), respectively for the threshold values of recursive residuals being 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0.

These binary classification based on minute interval is then applied to tick-base limit orders at the submission time. If a limit order is submitted in a minute interval at which the recursive residual from order flow regression exceed the threshold value, $INTERV_i$ takes the value of one and zero otherwise. The equation (4) is estimated with the tick data on September 15, 2010.

$$d_i^{se} = \beta_1 Vol_i + \beta_2 Gap_i + \beta_3 Depth_i + \beta_4 Calm_i + \beta_5 INTERV_i + \varepsilon_{t^s(i)} \qquad (4)$$

In Table 6 the estimated results of equation (4) is presented. The result of equation (3), without $INTERV_i$ variable in equation (4), is provided as specification (i) for comparison. Specification (ii) through (vii) include an intervention dummy variable, *INTERV*, which takes value of one when a recursive residual exceeds respectively the threshold value of 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0.First, *INTERV* variable is statistically significant for all specifications. The magnitude of impact, when interventions (and lingering post-intervention effect) are observed in the market, is the reduction of about 27 to 44 seconds in the life-time of limit orders. This is consistent with the result in Fong and Liu (2010) that limit order cancellations and revisions increase with the market volatility. Second, the magnitude of impact on reducing the life-time is monotonically larger when the threshold for recursive residuals becomes greater. The greater volatility in exchange rate caused by interventions affects existing orders to be canceled or revised. Third, a relatively moderate size of threshold, i.e., specification (iii) is chosen best for our model by the Schwarz BIC. For this specification, only 9.3 percent of the entire sample is designated as interventions or post-intervention effects. Finally, we note, however, the increase in terms of overall fitness of regression is only marginal.

In Table 7 the estimated results of equation (4) on the other intervention days in 2003 and 2004 are provided. For the estimations in Table 7, the comparison with 2010 intervention should be made with specification (vii) in Table 6 because the threshold value of 3 is used. Two findings are noteworthy. First, all intervention variables are consistent with expected negative sign and statistically significant at one percent leve. Second, the most distinct feature appears between post-crisis period and pre-crisis period interventions. The difference in the magnitude of intervention impact on reducing the life-time of limit orders is much greater in the pre-crisis period. The impact of intervention is about five to ten times greater in the pre-crisis period.

7. Robustness checks

In this section, we check how reliable our results are by estimating the same regressions for non-intervention days as well as using other criteria for constructing intervention variables.

7-1. Non-intervention days

So far our analysis is solely based on the days intervention actually occurred. This selection bias may bring spurious results of the effectiveness of intervention on reducing the life-time of limit orders. The reduction of the life-time may be caused by factors other than intervention activities and the analysis of non-intervention days may generate the similar results in which large recursive residuals simply reduce the life-time of limit orders without central bank involvements. For non-intervention days, we selected the following four days: September 8, 2010 (a week before the intervention); September 14 and 16, 2010 (one day before and after the intervention); and September 22, 2010 (a week after the intervention).

The estimated results are presented in Table 8. Similarly in Table 7, we chose the threshold value of 3. First, unlike intervention days, not all control/auxiliary variables are statistically significant. *Gap* and *Depth* are not statistically significant while *Vol* and *Calm* are consistent with expected sign and statistically significant. Second, the fitness of regressions on non-intervention days are much lower than intervention days. Therefore we have some evidence that intervention activities by the central bank may strengthen financial behavior relationship besides the effectiveness of intervention variable itself. Third, *INTERV* variables become insignificant for two days. This is as expected because large recursive residual is just mere statistical phenomena in non-intervention days. However, the effectiveness of *INTERV* variables on September 8, 2010 and September 14, 2010 are disturbing because these days are strictly prior to intervention activities and difficult to be explained by intervention after-effects. We return to this issue in the next subsection by using different *INTERV* variables.

7-2. Different criteria for constructing INTERV variables

In Table 7 and 8 results only by threshold value of 3 for *INTERV* are provided to make comparison easier among different dates. Regression model (4) is estimated for all dates (both intervention days and non-intervention days) by using different threshold values for *INTERV*. P-values for *INTERV* are reported in Table 9 and different threshold values for recursive residuals are denoted by RR with corresponding two digit number.

For all intervention days, intervention binary variables, constructed by using thresholds of large recursive residuals, are statistically significant at one percent level regardless of threshold values. In contrast, for non-intervention days, the results are unstable at the best. For each threshold value, there are always two dates (out of four) in which *INTERV* variables are not statistically significant even at ten percent level. For each date, the statistical significance of *INTERV* varies widely by threshold values. We confirmed the results presented in both Table 7 and 8 remain qualitatively the same for other threshold values of *INTERV*.

One possible critic of using recursive residuals is a possible bias introduced in recursive residuals for the later observations after interventions if a structural change actually occurred in the relationship between exchange rate return and order flow. In addition to using recursive residual method in which estimation sample extends for later observations, we also used forecast errors with rolling windows of sample periods. Different size of windows (60, 120, 180, and 240 minutes) and different size of threshold values (2.0, 2.5, 3.0, 3.5, and 4.0) are used to construct corresponding *INTERV* variables. These results are also shown in Table 9 for each criteria denoted by FE plus corresponding windows (in terms of hours) and two digits indicating threshold values.

The comparison between results in intervention days and non-intervention days is quite contrast that statistical significance of *INTERV* seems at random at the best for non-intervention days whereas *INTERV* variables are statistically significant at one percent level regardless of window size and threshold values. With these robustness checks, this study find the strong supporting evidence that intra-day interventions significantly affect the limit order behaviors of financial institutions in the foreign exchange markets.

8. Conclusions

In this paper, we investigate the impact of the BOJ intervention on September 15, 2010 on trading activities on the yen/dollar market of the EBS. The BOJ had refrained from interventions for more than six years and the world is hit severely by the global financial crisis during this period. We also investigate five intervention days that occurred in 2003 and 2004.

Given the major role of limit orders on the EBS, it is imperative to investigate the effect of limit orders on the foreign exchange market. Contrary to previous studies, the net order flow in this study is constructed from limit orders rather than from market orders, which are observationally equivalent to transaction data. The main contributions of the investigation on the relationship between order flow and exchange rate are the following two points. First, we find that the order flow of limit orders has a positive impact on the exchange rate, i.e., an excess of bid over offer orders appreciate the value of the US dollar against the Japanese yen. This is consistent with many previous studies which use the market order (transaction) definition of order flow. Second, we find that the relationship between order flow and market return on the dollar/yen exchange market experiences a break down following the unexpected and very high volume of offer/sell orders following the BOJ interventions. The recursive residuals detect the timing of the BOJ interventions with striking clarity. A simple methodology is proposed to detect the exact timing of interventions. We propose to construct an intervention proxy variable which takes the value of one when a recursive residual from the order-flow-exchange-rate regression exceeds the threshold value.

Using the EBS data provided by the ICAP, we are able to track the termination of limit orders (by either transaction or cancellation) and we measured the lifetime of limit orders. We find interventions, detected by the proposed methodology, significantly reduce the life-time of limit order in the market by about 27 to 44 seconds while controlling for the volume, the gap between quote and market price, the slower pace of the market, and large outstanding orders in the order book.

As robustness checks, we also applied the same methodology to non-intervention days and could not find the similar relationship between large recursive residuals (from exchange rate return regressions) and the life-time of limit orders. These results stand robust to regardless of various ways to construct intervention variables.

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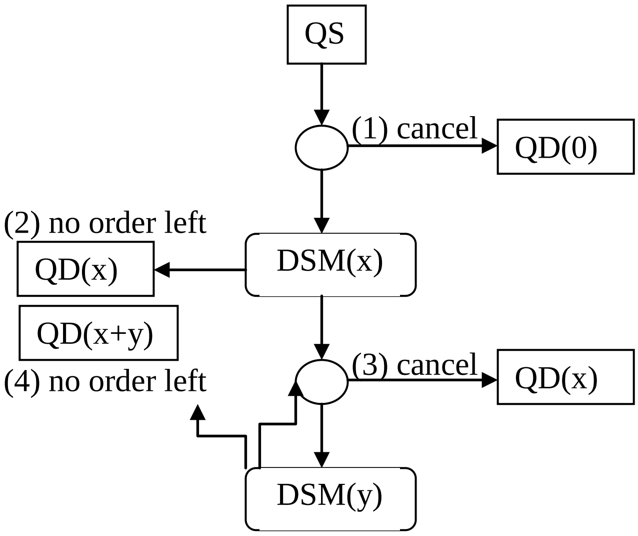
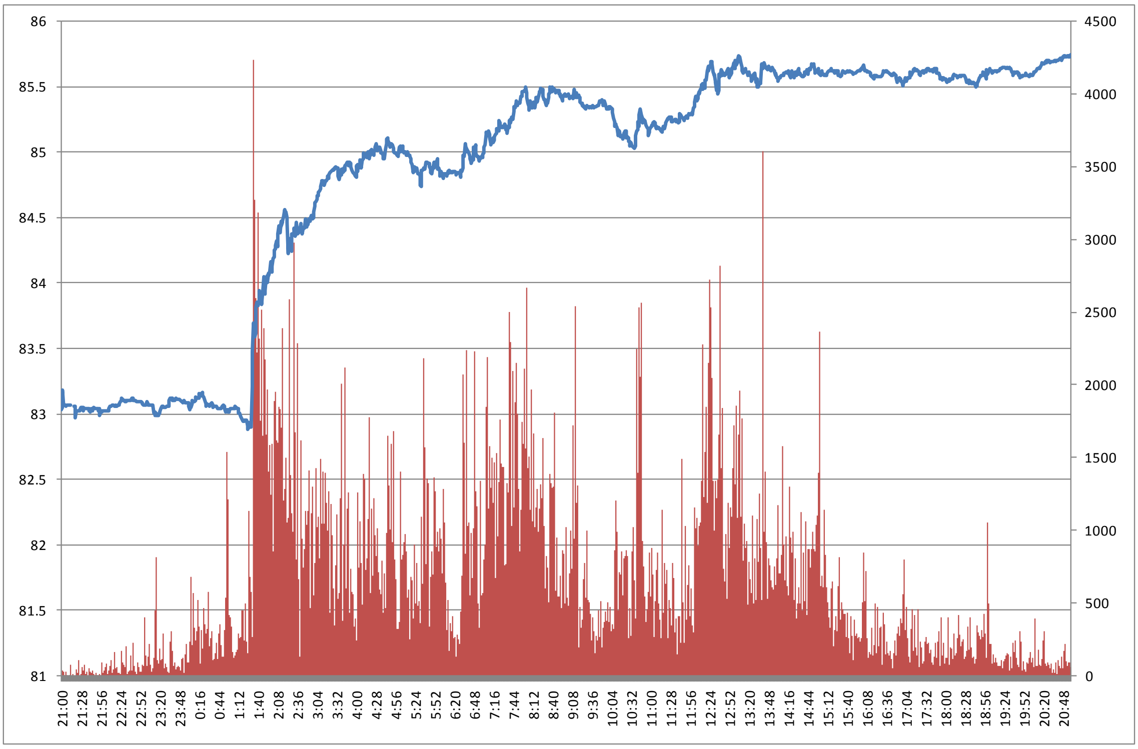
Figure 1. Records of quotes on the EBS Spot market



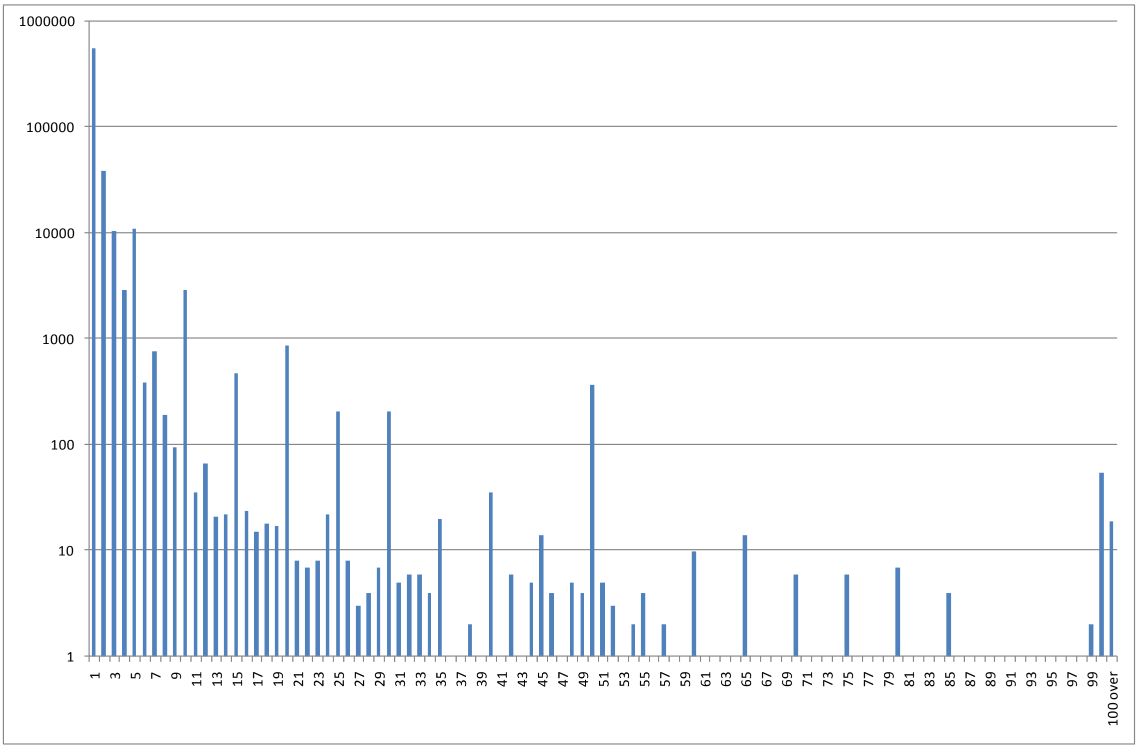
Note: QS indicates the start of the quote. QD indicates the end of the quote. DSM indicates a transaction. There are four cases for the life of quotes. (1) a quote is deleted by cancellation; (2) a quote is filled with either another quote or a market order; (3) a quote is canceled after a part of the order is executed; (4) a quote is filled by multiple transactions.

Figure 2. Exchange rate and limit-order volume plotted against minute interval (September 15, 2010)



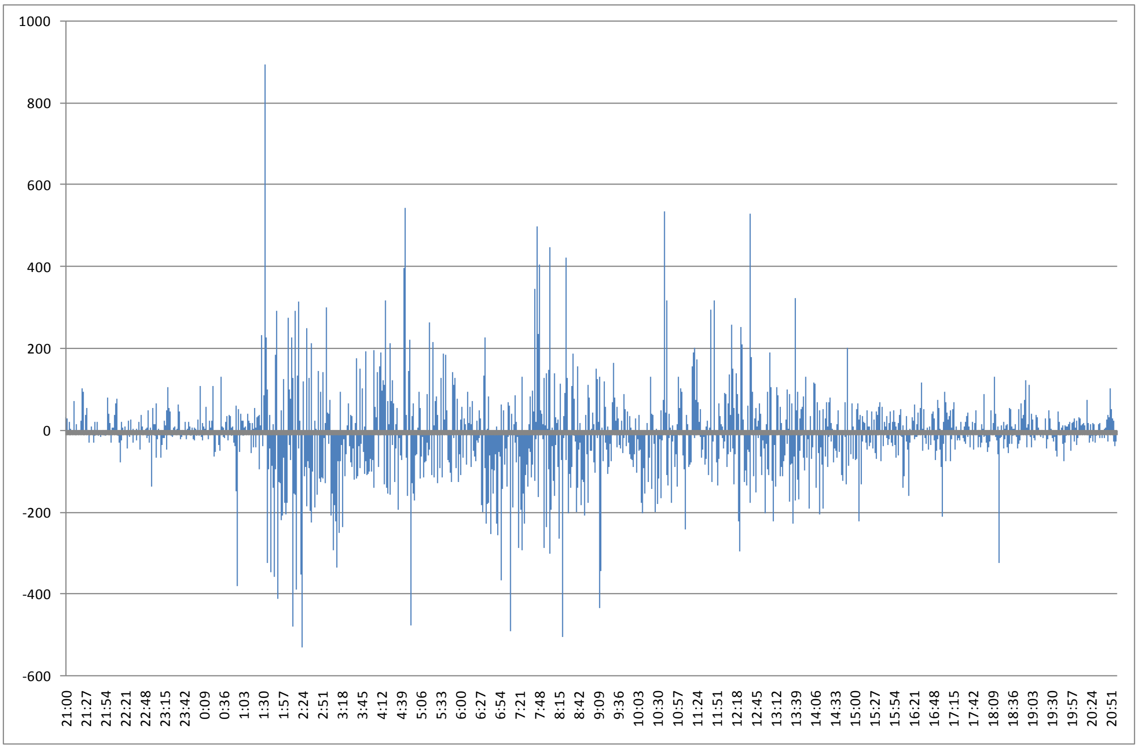
Note: The minute interval sums all limit order volumes in a one minute period. For example, the volume at 23:02 covers all transactions that occur between 23:02:00 and 23:02:59. The minute interval exchange rate is the mid-rate of the latest best bid-ask rates during the current minute. The exchange rate is scaled on the left vertical axis and the limit-order volume (bar) is scaled on the right vertical axis.

Figure 3. The distribution of order size (September 15, 2010)



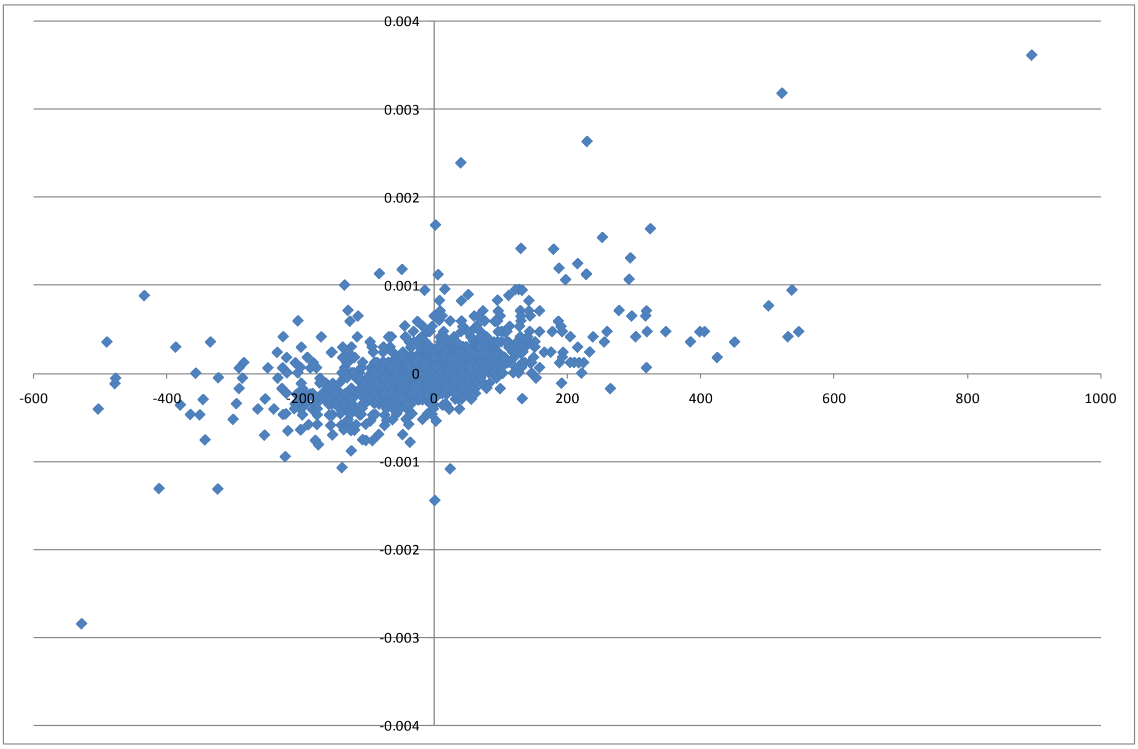
Note: All limit orders on the JPN/USD spot market from 21:00:00 (GMT) on September 14 to 20:59:59 (GMT) on September 15, 2010. The number of data points is 625,725. The vertical axis is the number of orders, shown on a log scale. The size of orders on the horizontal axis is marked in US million dollars. Over 85 percent of all orders have a minimum value of 1 million US dollars.

Figure 4. Quote order flow (September 15, 2010)



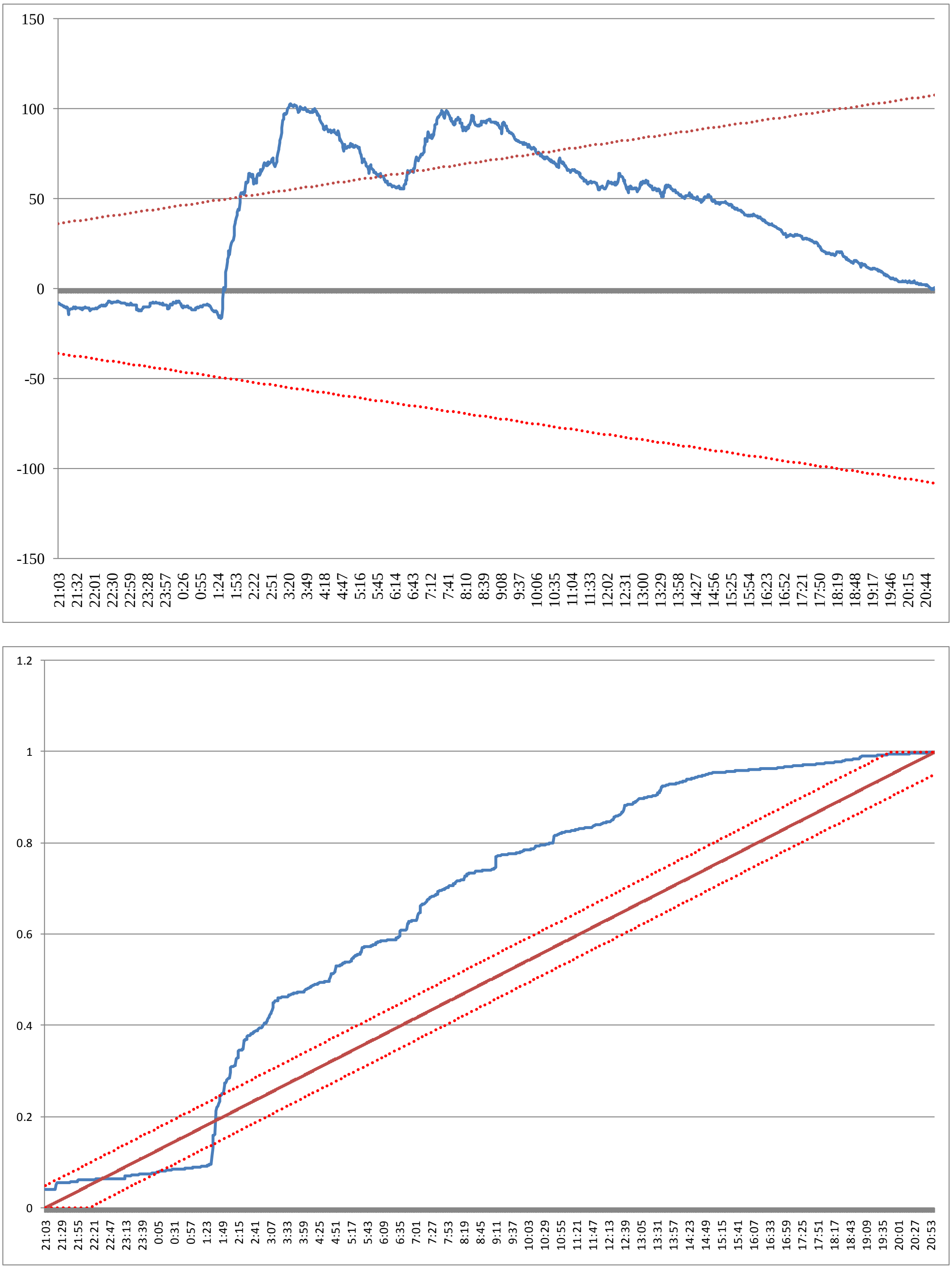
Note: The net quote order flow is defined as the bid (dollar purchase) minus offer (dollar sales). The minute interval sums all quote volumes for the one minute.

Figure 5. Exchange rate and order flow (September 15, 2010)



Note: The one-minute change measured in log yen/dollar is plotted on the vertical axis, and the net (quote) order flow is plotted on the horizontal axis.

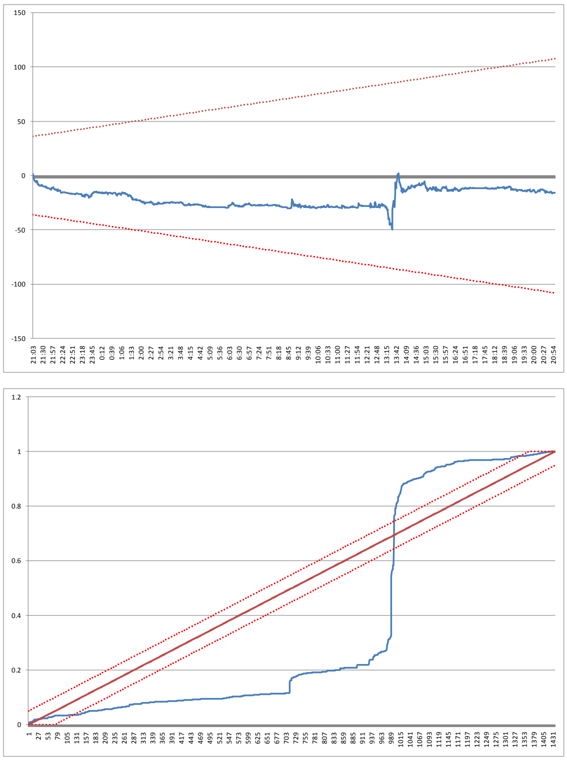
Figure 6. The CUSUM and CUSUM square tests (September 15, 2010)



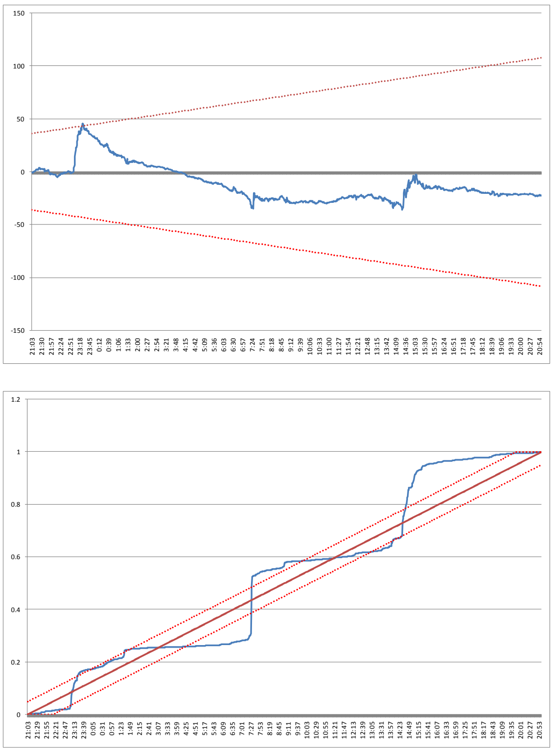
Note: The solid line represents the accumulated sum of the forecast residuals (upper panel) and the squared forecast residuals (lower panel), and the dotted lines represent the 95 percent upper and lower bounds.

Figure 7. The CUSUM tests for pre-crisis intervention days

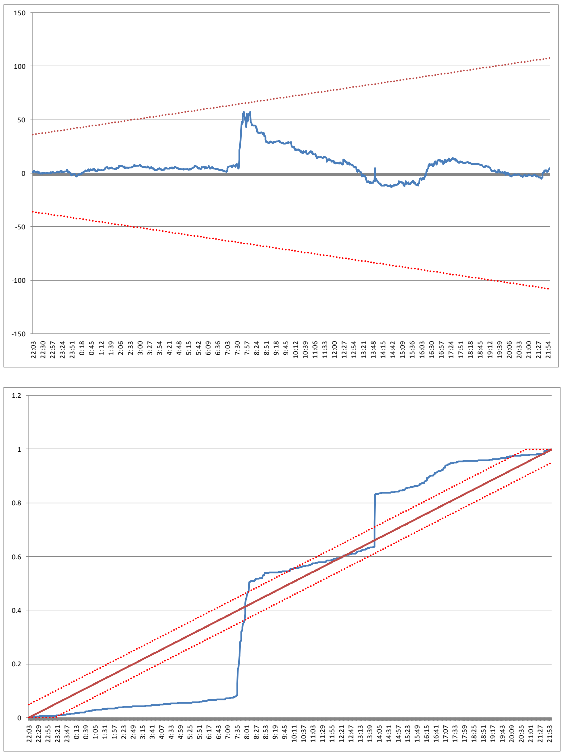
Panel A: September 12, 2003



Panel B: September 30, 2003



Panel C: December 10, 2003



Panel D: January 9, 2004

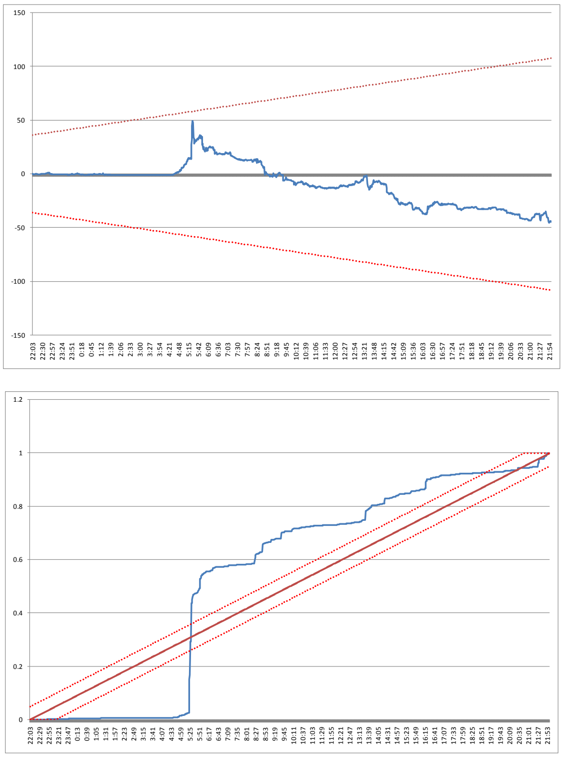
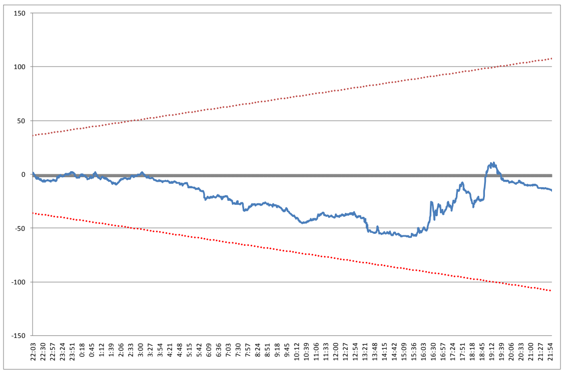
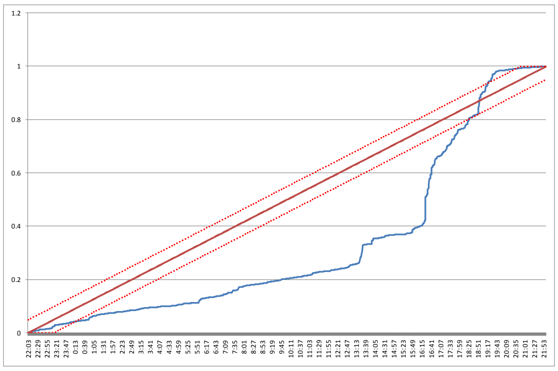


Figure 7. (Continued)

Panel E: March 5, 2004





Note: The solid line represents the accumulated sum of the forecast residuals (upper figure) and the squared forecast residuals (lower figure), and the dotted lines represent the 95 percent upper and lower bounds.

Table 1. Order size by hour (September 15, 2010)

	panel (A)				panel (B)		panel (C)					
							10over			50over		
hour	all	bid	offer	bid-offer	average	max	all	bid	offer	all	bid	offer
21	689	374	315	59	2.09	60	23	22	1	4	4	0
22	2,823	1,299	1,524	-225	1.33	75	30	19	11	4	2	2
23	5,921	2,982	2,939	43	1.16	51	35	24	11	2	1	1
0	14,612	7,396	7,216	180	1.27	100	136	61	75	13	7	6
1	47,334	22,087	25,247	-3160	1.42	300	707	439	268	63	42	21
2	50,029	23,287	26,742	-3455	1.41	250	668	398	270	87	52	35
3	36,076	17,119	18,957	-1838	1.38	250	503	207	296	33	22	11
4	30,433	14,641	15,792	-1151	1.57	250	505	261	244	85	68	17
5	35,088	16,629	18,459	-1830	1.29	250	307	215	92	25	20	5
6	33,452	16,095	17,357	-1262	1.30	95	226	135	91	10	2	8
7	51,683	25,423	26,260	-837	1.45	100	624	308	316	44	25	19
8	41,633	20,326	21,307	-981	1.47	411	348	169	179	35	22	13
9	23,053	11,409	11,644	-235	1.41	100	141	70	71	13	9	4
10	31,100	14,864	16,236	-1372	1.37	150	196	120	76	11	9	2
11	19,922	9,898	10,024	-126	1.43	65	93	52	41	15	13	2
12	56,145	27,780	28,365	-585	1.34	430	467	263	204	27	22	5
13	42,465	20,630	21,835	-1205	1.29	100	239	129	110	14	7	7
14	39,020	19,064	19,956	-892	1.22	100	141	84	57	12	8	4
15	20,537	10,209	10,328	-119	1.26	80	66	36	30	8	2	6
16	12,911	6,460	6,451	9	1.21	60	49	11	38	3	1	2
17	9,813	4,901	4,912	-11	1.14	50	27	15	12	2	2	0
18	11,085	5,664	5,421	243	1.17	199	41	14	27	7	4	3
19	5,955	3,107	2,848	259	1.17	50	17	1	16	1	0	1
20	3,946	2,054	1,892	162	1.35	40	36	18	18	0	0	0
Total	625,725	303,698	322,027				5,625			518		

Note: The figures in panels (A) and (C) are the number of orders submitted within one hour. In panel (B), the unit is one million US dollars for the average and maximum values. In panel (C), 10 over and 50 over represent the number of orders greater than or equal to 10 and 50 million US dollars, respectively.

Table 2. The per minute change in yen-dollar on net order flow (September 15, 2010)

	post-crisis
	2010Sep15
constant	0.00004006***
	(0.00000792)
OF	0.00000180***
	(0.00000019)
Adj.R2	0.31
NOB	1439

	pre-crisis				
	2003Sep12	2003Sep30	2003Dec10	2004Jan9	2004Mar5
constant	0.00000142	0.00001117	0.00000805	-0.00000618	0.00000283
	(0.00000335)	(0.00000811)	(0.00000508)	(0.00000567)	(0.00000386)
OF	0.00000072***	0.00000186***	0.00000121***	0.00000181**	0.00000037**
	(0.00000024)	(0.00000059)	(0.00000034)	(0.00000084)	(0.00000015)
Adj.R2	0.07	0.13	0.10	0.29	0.04
NOB	1439	1439	1439	1439	1439

Note: The dependent variable is the per minute change in the log of the yen/dollar exchange rate, and a positive value indicates dollar appreciation. The net quote order flow is defined as the bid (dollar purchase) minus offer (dollar sales), and a positive value indicates the net purchase order measured in dollars. The standard errors in parenthesis are robust to heteroskedasticity. *, **, and *** denote statistical significance at the ten-, five-, and one-percent levels, respectively.

Table 3. Descriptive statistics (September 15, 2010)

	mean	s.d.	min	max
d_i^{se} (lifetime of limit order)	41.9	526	0.001	85716
Vol (volume)	1.36	2.70	1	430
Gap (difference between the quote and market price)	0.0225	0.0696	-0.3	33.5
Depth (the volume sum in the order book)	178	86.2	4	845
Calm (previous durations for consecutive orders)	2.15	5.60	0.009	508

Note: The number of observations is 625,573, excluding the first 29 observations.

Table 4. The lifetime of limit orders (September 15, 2010)

	all orders		canceled orders	
	coef.	s.d.	coef.	s.d.
Vol	9.898	(0.226)***	13.316	(0.325)***
Gap	2610.5	(8.83)***	2498.4	(9.04)***
Depth	-0.182	(0.0036)***	-0.217	(0.004)***
Calm	5.763	(0.108)***	5.211	(0.119)***
adj. R^2	0.13		0.13	
NOB	625,573		553,732	

Note: All orders includes realized and canceled orders. The first 29 observations are dropped to construct the best bid-ask quotes. S.d. is the standard deviation robust to heteroskedasticity. *, **, and *** denote statistical significance at the ten-, five-, and one-percent levels, respectively.

Table 5. The lifetime of limit orders (prior to the subprime financial crisis)

all limit orders

	2003Sep12	2003Sep30	2003Dec10	2004Jan09	2004Mar05
Vol	31.28***	3.67***	5.83***	9.64***	11.73***
	(1.48)	(0.45)	(0.56)	(0.47)	(0.37)
Gap	10,895.80***	4,913.44***	7,232.77***	5,678.54***	7,855.36***
	(165.96)	(44.74)	(68.92)	(59.70)	(78.00)
Depth	-0.26***	-0.42***	-0.18***	0.09***	-0.05***
	(0.04)	(0.05)	(0.02)	(0.01)	(0.00)
Calm	1.91***	1.12***	1.01***	1.35***	0.74***
	(0.10)	(0.07)	(0.06)	(0.08)	(0.07)
Adj.R2	0.21	0.19	0.20	0.21	0.20
NOB	21,674	53,085	45,303	42,825	48,912

canceled limit orders

	2003Sep12	2003Sep30	2003Dec10	2004Jan09	2004Mar05
Vol	7.80**	3.52***	8.57***	22.42***	16.94***
	(3.15)	(0.96)	(1.07)	(0.92)	(0.66)
Gap	11,022.60***	5,142.72***	7,502.63***	5,439.98***	7,280.17***
	(224.20)	(67.28)	(92.84)	(78.09)	(102.59)
Depth	-0.35***	-0.70***	-0.30***	0.14***	-0.07***
	(0.06)	(0.10)	(0.03)	(0.02)	(0.01)
Calm	2.61***	1.34***	0.89***	0.95***	0.47***
	(0.16)	(0.12)	(0.10)	(0.13)	(0.12)
Adj.R2	0.21	0.19	0.21	0.23	0.19
NOB	10,647	25,242	26,240	23,793	28,279

Note: All limit orders include realized and canceled orders. The first 29 observations are dropped to construct the best bid-ask quotes. S.d. is the standard deviation robust to heteroskedasticity. *, **, and *** denote statistical significance at the ten-, five-, and one-percent levels, respectively.

Table 6. The effect of intra-day interventions on the life-time of limit order

	(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)
Vol	9.90***	10.25***	10.24***	10.23***	10.17***	10.11***	10.08***
	(0.23)	(0.23)	(0.23)	(0.23)	(0.23)	(0.23)	(0.23)
Gap	2,608.26***	2,620.07***	2,620.02***	2,619.11***	2,617.12***	2,615.12***	2,614.08**
	(8.83)	(8.85)	(8.84)	(8.84)	(8.84)	(8.84)	(8.84)
Depth	-0.19***	-0.15***	-0.16***	-0.17***	-0.17***	-0.18***	-0.18***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Calm	4.83***	4.77***	4.74***	4.75***	4.77***	4.78***	4.78***
	(0.09)	(0.09)	(0.09)	(0.09)	(0.09)	(0.09)	(0.09)
INTERV		-26.89***	-32.73***	-36.83***	-39.91***	-41.77***	-44.09***
		(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Adj.R2	0.13	0.13	0.13	0.13	0.13	0.13	0.13
SBIC	4763180	4762950	4762930	4762940	4762980	4763020	4763040
NOB	625571	625571	625571	625571	625571	625571	625571

Note: The first 31 (not 29) observations are dropped for all specifications to have equal number of observations. The first specification is the same as in Table 4 except estimators are a little different due to the difference in the number of observations. Specification (ii) through (vii) include an intervention dummy variable, *INTERV*, which takes value of one when a recursive residual exceeds respectively the threshold value of 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0.

Table 7. The effect of intra-day interventions (pre-crisis periods)

	2003Sep12	2003Sep30	2003Dec10	2004Jan09	2004Mar05
Vol	33.59***	4.30***	7.42***	10.48***	12.03***
Gap	11,007.18***	4,980.00***	7,461.90***	5,744.69***	7,901.93***
Depth	-0.23***	-0.22***	-0.15***	0.10***	-0.05***
Calm	1.82***	1.01***	0.95***	1.31***	0.74***
INTERV	-314.08***	-172.20***	-292.88***	-293.63***	-168.19***
Adj.R2	0.21	0.19	0.21	0.21	0.20
NOB	21672	53083	45301	42823	48910

Note: An intervention dummy variable, *INTERV*, which takes value of one when a recursive residual exceeds 3.

Table 8. Robustness check (non-intervention days)

	2010Sep8	2010Sep14	2010Sep16	2010Sep22
Vol	66.62***	33.11***	33.75***	20.22***
Gap	0.00	0.00	0.01	0.00
Depth	-0.21***	0.02	0.03	0.09***
Calm	3.54***	3.11***	4.19***	3.39***
INTERV	-19.88***	-21.10***	17.86	-11.33
Adj.R2	0.02	0.01	0.01	0.01
NOB	307184	315216	328310	290775

Note: An intervention dummy variable, *INTERV*, which takes value of one when a recursive residual exceeds 3.

Table 9. Robustness check (different criteria): p-values for *INTERV* variable

Large error criteria	Intervention Days						Non-intervention Days			
	2003Sep12	2003Sep30	2003Dec10	2004Jan09	2004Mar05	2010Sep15	2010Sep8	2010Sep14	2010Sep16	2010Sep22
RR05	0.000	0.000	0.000	0.000	0.000	0.010	0.738	0.000	0.003	0.670
RR10	0.000	0.000	0.000	0.000	0.000	0.004	0.225	0.328	0.000	0.210
RR15	0.000	0.000	0.000	0.000	0.000	0.002	0.008	0.122	0.000	0.759
RR20	0.000	0.000	0.000	0.000	0.000	0.001	0.016	0.832	0.000	0.109
RR25	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.384	0.095	0.269
RR30	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.000	0.111	0.498
RR35	0.000	0.000	0.000	0.000	0.000	0.000	0.163	0.008	0.602	0.000
RR40	0.000	0.000	0.000	0.000	0.000	0.003	0.198	0.002	0.594	0.000
FE1_20	0.000	0.000	0.000	0.000	0.000	0.002	0.615	0.001	0.000	0.024
FE1_25	0.000	0.000	0.000	0.000	0.000	0.000	0.506	0.704	0.000	0.033
FE1_30	0.000	0.000	0.000	0.000	0.000	0.000	0.295	0.518	0.002	0.003
FE1_35	0.000	0.000	0.000	0.000	0.000	0.000	0.039	0.631	0.002	0.023
FE1_40	0.000	0.000	0.000	0.000	0.000	0.000	0.103	0.574	0.000	0.028
FE2_20	0.000	0.000	0.000	0.000	0.000	0.001	0.205	0.076	0.185	0.273
FE2_25	0.000	0.000	0.000	0.000	0.000	0.001	0.155	0.288	0.361	0.391
FE2_30	0.000	0.000	0.000	0.000	0.000	0.000	0.258	0.922	0.527	0.078
FE2_35	0.000	0.000	0.000	0.000	0.000	0.000	0.014	0.831	0.473	0.234
FE2_40	0.000	0.000	0.000	0.000	0.000	0.000	0.099	0.122	0.070	0.234
FE3_20	0.000	0.000	0.000	0.000	0.000	0.000	0.133	0.071	0.507	0.734
FE3_25	0.000	0.000	0.000	0.000	0.000	0.000	0.208	0.880	0.312	0.460
FE3_30	0.000	0.000	0.000	0.000	0.000	0.000	0.721	0.037	0.546	0.062
FE3_35	0.000	0.000	0.000	0.000	0.000	0.000	0.168	0.026	0.188	0.411
FE3_40	0.000	0.000	0.000	0.000	0.000	0.000	0.171	0.006	0.874	0.000
FE4_20	0.000	0.000	0.000	0.000	0.000	0.001	0.011	0.253	0.049	0.238
FE4_25	0.000	0.000	0.000	0.000	0.000	0.000	0.210	0.521	0.034	0.496
FE4_30	0.000	0.000	0.000	0.000	0.000	0.000	0.150	0.033	0.036	0.785
FE4_35	0.000	0.000	0.000	0.000	0.000	0.001	0.313	0.000	0.333	0.730
FE4_40	0.000	0.000	0.000	0.000	0.000	0.000	0.313	0.000	0.897	0.000
over 10%	0	0	0	0	0	0	20	15	14	17

Note: Recursive residual is used for RR variables and forecast errors with rolling windows for FE variables. The figures are p-values for *INTERV* variable in life-time equations.