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ABSTRACT

This paper examines the consequences of the 2015 reform on the London fixing in the interbank forex market, which resulted from finding and imposing a penalty on banks' collusive behavior around the fixing window. The banks changed their behavior after the reform, and the volume spike in the fixing window disappeared. However, the anomalies on price dynamics reported in the previous literature still exist, and banks' passive trading strategy generates another predictability in the price movement. A theoretical model of optimal execution is used to calibrate the execution of fixing transactions by banks, and evaluate the increase in the cost and risks of fixing trades incurred by the banks' behavior. This paper is the first to examine the efficiency of banks' behavior after the reform. The volume pattern during the fixing time window suggests that banks, by avoiding (even the appearance of) collusion, now incur the costs of executing customers' orders.

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1 Introduction

This paper examines the exchange rate (price) and trading volume behaviors in pre-, during, and post-fixing time windows in the London market, with a comparison of periods before and after the reform of the fixing method in February 2015. The reform was brought about by the discovery of banks colluding before the start of fixing window by sharing information regarding customers' orders. Banks were heavily penalized for the behavior. The banks significantly modified their trading strategies around the fixing window after the reform, which changed the fixing window from 1 minute to 5 minutes. We document the changes in the price and volume patterns before and after the reform, and evaluate those consequences using a theoretical model of optimal execution. This paper is the first to examine the efficiency of banks' behavior after the reform. The volume pattern during the fixing time window suggests that banks, by avoiding (even the appearance of) collusion, now incur the costs of executing customers' orders.

"Fixing" is a practice in the foreign exchange market to determine the bid-ask mid-point exchange rate (fixing price) in a transparent formula at a pre-determined time of the day. The fixing price is used to the settlement of foreign exchange transactions between banks and bank's customers including broker-dealers, institutional investors, insurance companies, exporters and importers and for valuation of foreign securities and mutual funds, as well as derivatives on the financial institutions' balance sheets. Using the fixing price, bank customers are reassured in that they are not discriminated among themselves by the bank, and valuations reflect the market fairly and transparently.

In London, WM/Reuters announces the fixing price just after 4:00 pm, based on transaction prices in the one-minute window around 4:00 pm (that is, from 15:59:30 to 16:00:30). The WM/Reuters 4 pm fixing rate is calculated as the median of sampled transactions during the one-minute window. The WM/Reuters fix is widely used as the exchange rates for customer trades in the London and New York markets, and as the exchange rate to value financial products on the book. In the 24-hour cycle, transaction volumes are highest around 1:00 pm to 4:00 pm in London (8 am to 11:00 am in New York). After the 4:00 pm fixing in London, transaction volumes and price volatility quickly diminish. The banks have accumulated the customer orders of the day by 4:00 pm London so that there will be no large exposures after the 4:00 pm fixing.

The fixing poses as a profit opportunity for banks if they can manipulate the fixing price away from the prevailing market price. When a bank realizes that the bank was asked to sell more dollars than to buy dollars from bank's customers, it may profit from bidding up the fixing price higher (dollar appreciation) than prices of other times of the day. Suppose that the bank can quote 100.10 yen/dollar for retail customers as the fixing price, while the bank can buy the dollar in the interbank market at 100.00 yen, then the bank can earn the extra profit of 0.1 yen per dollar. However, for this to transpire, the fixing price had to be "manipulated" to be higher than other times (around the fixing time), and the amount of net buy from retail customers had to be known. Such an attempt by banks to affect the market price before the fixing is called "pre-hedge". Whether this can be done in a deep liquid market like the foreign exchange market is a big question.

The banks' behavior around the London WM/Reuters 4:00 pm fixing is a target of an investigation by regulatory authorities. We summarized the timeline regarding the Forex benchmark scandal in Table 1. The investigation was first reported in the media on June 12, 2013, followed by other occasional media reporting.[1] In the wake of these investigations, several traders were suspended and resulted in penalties imposed on several large banks in London trading. In addition, a Bank of England employee was suspended.[2] There was evidence of information exchange on customer order flows of several large banks, which constituted collusion. However, no direct evidence was presented (in public) in the manner of price behavior or manipulation.

The investigations resulted in large fines on several banks for a collusion through the sharing of customers' order information.[3] Evidence mostly based on the readings of chat room records was supplemented by case studies of particular banks behavior in particular days. In essence, when banks can figure out via chats customer order imbalances then banks can bid up or down depending on the direction of imbalances, to manipulate the fix rate that was determined as a median of transactions exchange rates (price) during the fixing window that was for one minute around 4 pm.

In response to the concerns over the Forex benchmarks, the Financial Stability Board (FSB) formed a working group that undertook an analysis of the Forex market structure and incentives regarding the particular trading activities around the fixings. The working group published a report in July, and the FSB published a final report in September 2014 (Financial Stability Board (2014)). The report points out the large spike in trading volume in and around the fixing window and expresses concern over the incentive for dealers to try to influence the exchange rate. The recommendations by the group included widening the fixing window (from 1 minute to 5 minutes) and minimizing the conflicts of interest arising from managing customer flow within banks.

On February 15, 2015, based on the FSB recommendations of September 2014, the WM widened the fixing window in London that is used to calculate benchmark rates from 1 minute for

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[1] On June 12, 2013, *Bloomberg* broke the story first, and followed by *Financial Times*. Subsequent reporting was in *Bloomberg* (2013, August 27, and December 19), *Financial Times* (2014, February 16, March 21, March 25, March 27, March 31) and Reuters (2014, March 11).

[2] According to the *Economist* on March 8, 2014: "On March 5th the Bank of England announced that it too had suspended an official following an internal investigation."

[3] On November 12, 2014, the UK Financial Conduct Authority (FCA) imposed £1.1 billion ($1.7 billion) fines on five banks "for failing to control business practices in their G10 spot foreign exchange trading operations": Citibank $358 million, HSBC $343 million, JPMorgan $352 million, RBS $344 million and UBS $371 million. See https://www.fca.org.uk/news/press-releases/fca-fines-five-banks-%C2%A311-billion-fx-failings-and-announces-industry-wide. On May 20, 2015, FCA imposed £284 fines on Barclays Other authorities, including Federal Reserves, Department of Justice, and Commodity Futures Trading Commission (CFTC), imposed fines. In total, about 10 billion dollars were imposed on 7 banks.

‘traded’ currencies and 2 minutes for ‘non-traded’ currencies, to 5 minutes for all currency pairs. We will take the change on February 15, 2015 as the “reform” in the rest of the paper.

In the 2015 FSB progress report, they examined the EBS and Reuters tick data over three months after the reform. They find that the increase of trading volume around the fix spread over 5 minutes after the reform, from the one-minute before the reform, and the liquidity (measured by the bid-ask spread) also increased in the five minutes fixing window. More importantly, they report that the trading volume now spread more evenly over time, while it was more concentrated at the beginning of the fixing window before. They relate this finding to the increased use of algorithmic execution. They also note on the “pre-hedging” behavior by banks (Financial Stability Board (2015)): “A rise in trading volume is evident once the fixing window is open, with little or no pre-hedging taking place through either the EBS or TRM platforms.”

As another result of the reform, they report the charging for fixing transactions by sell-side banks. Because banks suffer from the risk that the fixing transaction causes, which might be covered by the misconduct before, after the reform, their pricing methodologies charge for fixing transactions, such as applying a bid-ask spread and charging a fixed fee.

The objectives of this paper are three-fold. First, we examine the price, volume, and liquidity behavior at the 4:00 pm “fixing” in London. In the literature, several papers have examined a 24-hour cycle of price volatility, bid-ask spread, and order flows, as well as volumes. This paper will extend what we know from the existing literature on high-frequency data to a specific institution of fixing. More specifically, we re-examine the anomaly of price behavior relating the fixing that was reported by Evans (2014). Second, we provide an evaluation of the reform, by analyzing data before and after the reform. This is an extension of the findings by Financial Stability Board (2015). Third, we provide a model-based analysis on the cost and risk that the banks pay for the fixing transactions.

The existing literature mostly focuses on the volume spikes around the fixing time. It is well known that transaction volumes tend to skyrocket at Tokyo 10 am fixing and London 4:00 pm fixing (Chaboud et al. (2004), Melvin and Prins (2015)).[4] Associated with this volume spike, the price is also affected (Evans (2014)). In contrast to the other market event such as macro announcements, the price jumps and spikes during the fixing window, representing only temporary order imbalances and liquidity shortages, which is expected not to result in such jumps to a new equilibrium.

Before the reform, the price and volume behavior around the fix were very unusual. First, the path of price showed a reversal after the end of fixing the window, and the reversal is particularly reinforced at each end-of-month trading day (Evans (2014)).[5] Second, the volatility in pre- and the

[4] In addition to the London 4pm fixing, there are other times of the day that have spikes in trading volumes: Tokyo 9:55 am fixing, US macro announcement times, New York option cut at 3pm. For the Tokyo fixing, see Ito and Yamada (2016).

[5] Melvin and Prins (2015) also report the past positive equity return in a country is associated with the currency depreciation of that country at the end of month fixing. Equity investors hedge the

post-fixing period is abnormally high (Evans (2014)). This imposes a doubt on the fixing rate as a fair benchmark of the intraday exchange rate. Again, this unusually high volatility is more evident at end of month trading days. Third, the trading volume is the larger in the first-half of fixing window than that in the second-half. Supposedly, this fact relates to the pre-hedging behavior of banks.

Even after the reform, the total trading volume during the fixing window has not necessarily reduced. This implies that the demand for fixing trade is still high and the investigation on the unusual patterns at the fixing is necessary. We confirm that the second observation still holds. The first observation also holds but the pattern is relatively weakened, and the pattern also changed. The large part of the third observation disappeared.

Finally, we quantitatively evaluate the cost and risk for fixing traders. Although the changes in the patterns of liquidity provision are evident, the effect on total cost of fixing traders is still not clear. Related to this, most sell-side respondents to the Foreign Exchange Committee (FXC) surveys, conducted by the Federal Reserve Bank of New York, had largely implemented the recommendation to charge for fixing transactions for 4 pm London fixing, after the February 2015 reform (FSB 2015 document). Although the bid-ask spread during the fixing windows had decreased, the depth had become the thinner than before. Evaluation of cost for fixing traders is particularly important.

Based on the optimal execution model and using high-frequency data on the limit order book, we calibrate the behavior of fixing traders.[6] The calibration provides the predictions of trade pattern and the estimates of trading cost and risk. Our conclusion is that the reduction of transaction cost for fixing traders after the widening of the fixing window is not large enough to offset the increase of risk. Moreover, if the traders are not allowed, or are discouraged, to use pre-hedge, which is the prescription of the model, the transaction cost increases dramatically.

The rest of the paper is organized as follows. Section 2 will describe the EBS tick-by-tick data used in this paper. Section 3 will present econometric analysis on the exchange rate (price) and transaction volumes in the periods of "pre-", "during" and "post-" the fixing window. The regime change by the reform will be a main objective of the investigation. Section 4 will construct and examine the model of cost and risk from fixing trades for a bank. Section 5 will conclude.

2 Data

In this section, our data and their treatment are described. The main market exchange rate data come

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growth of equities of a foreign country by selling the currency of that country. The timing of the hedging trade is typically at the London fixing at the end of the month, generating the predictability of price around end of month fixing.

[6] Osler and Turnbull (2017) theoretically discusses banks' strategic behavior to generating the fixing anomalies. In contrast, our model aims to calibrate the dynamic of trade and does not focus on the strategic relationships between banks.

from the trading platform of EBS:[7]

- ICAP EBS Level 5 (or Level 2) data (proprietary data, purchased by the first author) from January 2, 2006 to June 30, 2016. Currency pairs: 'AUD-USD', 'EUR-GBP', 'EUR-JPY', 'EUR-USD', 'GBP-USD', 'USD-CAD', 'USD-CHF', 'USD-JPY'

The ICAP EBS Forex dataset contains the information of deals and quotes at each time-slice.[8] Each observation has time-stamped prices (transaction prices and limit order prices if available) and volume (transaction volumes, limit order volumes if available). The grid of time-slices has changed during the following periods: “one second” before January 22, 2008, “a quarter-second” from January 22, 2008 to August 31, 2009, and “a 100 millisecond” from August 31, 2009 to present. The minimum price unit, or pips, also has changed. It was traditionally two digits after the decimal point for USD/JPY and four digits after the decimal point for EUR/USD. It was decimalized (three digits for USD/JPY and five digits for EUR/USD) on March 7, 2011 and then rolled back to half pips after September 24, 2012.

The dataset has different levels of recording details: EBS Level 2 and EBS Level 5. In the Level 5 dataset, each observation of the deal has buyer-initiated and seller-initiated deal volumes. The database, however, omits certain deals that show multiple transactions between time slices. The observation at a time-stamp (HH:MM:SS for example) contains the deals that occur between t-1 and t, where t is by one second. The recorded transaction prices at the time slice are the most extreme ones (highest paid and lowest given) during the time slice (1-second window in Level 2).

The information of quote contains the limit order prices and volumes up to ten steps (tenth best) of the limit order book. This observation is a snapshot of the limit order book, which is recorded when any change occurs in the book. The dataset also contains quote counts. A quote count is the number of traders who are submitting limit orders at each step of the book.

Note that EBS allows negative spreads: the best ask price can be lower than the best bid price. This situation happens when the two entities at the book do not have credit lines. Also, when an observation has both a deal and a quote, the dataset does not specify the order of each transaction. This may affect the estimation results in a later section. We take the limit order information for every three seconds, and the trade volume information at time t is aggregated in the period [t, t+3sec].

3 Empirical Analysis

We implement three empirical experiments for examining the 2015 reform. First, we examine

[7] Observations on Saturdays and Sundays (at GMT) are dropped, and so are observations on Christmas and New Years days.

[8] The ICAP EBS Forex data is a high-frequency data, which needs data cleaning. We provided a detailed data cleaning process when we introduced the methodology.

whether the fixing rate properly represents the intraday rate. This follows the analysis of Evans (2014). Second, we examine the changes in intra-fixing dynamics of order flows and liquidity, which extends the analysis in FSB report. Lastly, we evaluate the transaction cost and risk of fixing to trade in the fixing window.

3.1 Fixing rate as an appropriate benchmark of intraday rate

Average price path and trading profit around the fix

Figure 1 shows the average path of spot rate for EUR/USD and USD/JPY in 20 minutes around 4 pm London time. The left panels show the sample before the reform, and the right panels are after the reform. The rates are the mid-price and are relative to their levels at 3:50 pm. The paths are conditional on (1) positive (or negative) pre-fix changes (over 10 minutes) at end of month (upper and lower solid); (2) positive and negative pre-fix changes on intra-month days (upper and lower dots); (3) pre-fix changes above the 75th (or below the 25th) percentile on intra-month days (upper and lower dash). The resolution of the x-axis is two seconds and the y-axis is basis points.

Before the reform, as Evans (2014) pointed, the average price path showed a small reversal after the end of fixing window: the rates tend to drop after rising toward the fix, and tend to rise after dropping towards the fix. The larger reversal is found at the end-of-month trading days than intra-month days. After the reform, although not as clear as before because of the insufficient sample size, this reversal looks still exist in both end-of-month and intra-month trading days. The reversal seems to happen at the end of fixing window (or 4:02 pm) for both intra-month and end of month samples, but the magnitude is relatively small.

The predictable pattern of price around the fixing can imply a profitable contrarian investment strategy: taking a long (short) position after the end of fixing if the rates fell (rose) towards the fix. Table 2 shows the profitability of this investment strategy for each currency pair for each end-of-month and intra-month trading day sample.[9] The holding length of 1, 5, and 10 minutes are examined and the average return in basis point is presented.

Before the reform, this strategy made a profit for major currency pairs (such as EUR/JPY, EUR/USD, USD/CHF, and USD/JPY) at the end-of-month trading days. In the intra-month sample,

[9] The precise definition of profit is as follows. The pre-fix return is measured as the log-difference of the price at 16:00:00 and the first-recorded price during 15:49:30 to 15:59:30. The post-fix return is measured as the log-difference of the last quotes before 16:00:30 and the last quotes before 16:00+X:30, where X is chosen from 1, 5, and 10 minutes. The pre-fix return is calculated by mid-quotes, and the post-fix return is calculated by bid or ask prices depending on the direction of trades (e.g., in case of taking a long position, using ask price for the starting price and using bid price for the liquidating price.) Thus we consider the transaction cost from bid-ask spreads.

the profitability does not exist. This profit considers the bid-ask spread and annualized Sharpe ratios, defined as $\text{average(return)}/\text{std(return)} \times \sqrt{252}$, are also high.[10] Thus, the profit is still large after considering the transaction cost and the risk.

After the reform, the end-of-month profitability is still available, consistent with the visual findings in Figure 1. While the profitability of holding one minute is no longer available, the profitability of 15 minutes holding becomes even stronger than before. In the intra-month sample, there are no profitability, the same as before the reform.

As shown in later sections, fixing traders have an incentive to “pre-hedge”; i.e., they order more aggressively in the earlier period in the fixing window. By doing this, they can reduce the transaction cost significantly. Since this concentration of trades in the beginning part of the fixing window tends to cause a temporal impact on price and the price is resilient, the price after the fixing trade tends to reverse. The restriction on pre-hedge may dampen the evident pattern of reversal that was observed in the before-the-reform period. The concentration of trading volume during the fixing window tends to produce the reversal of prices after the end of fixing window. This indicates that the liquidity provision may not be sufficiently large to prevent apparent profitability taking advantage of price spite and reversal, if one is certain of the direction of the spike beforehand.

Tail probability of Pre and Post-fix price changes

Evans (2014) reports a particular rise in pre- and post-fix volatility in days at end of month. The pre- and post-fix volatilities are measured by the frequency of days that the absolute changes in rates in pre or post-fix interval are larger than the 95 percentile of the distribution of those away from the fix. This measure is a tail probability of volatility.

Table 3 reports the tail probability of pre- and post-fix rate volatility. The value of 0.05 is expected to be in normal times, and the value larger than 0.05 indicates abnormally high volatility. Before the reform, the volatility was higher in the pre- and post-fixing period. This evidence is particularly pronouncing for the rate behavior near the fix, or one minute before (and after) the fixing window. In addition, the abnormal volatilities are intensified on days at the end of month. This end-of-month calendar effect supports the projection that the abnormal volatility relates to the demand for fixing trades, since we expect settling needs from exporters, importers, and bank customers in general, tend to rise at the end of month.

This abnormal volatility near the fixing window remains even after the reform. This evidence holds for both intra-month and end-of-month trading days. One difference is that the tail probabilities

[10] The profit presented at Table 2 is daily return. Since the return does not correlate over time, annualized Sharpe ratio is daily Sharpe ratio multiplied by the root of number of trading days (see Lo (2002) for the statistical background). This specification is the same as Evans (2014). A problem is that the end-of-month investment opportunity occurs monthly and multiplying one-year trading days exaggerates the magnitude of annualized Sharpe ratio.

for USD/JPY being relatively low. Another notable difference is that post-fix volatilities on major currency pairs becomes less persistent: The post-fixing tail probabilities over 15 minutes are mostly smaller than 0.1 for measure currencies, while those were larger than 0.1 before the reform.

In summary, the price changes around the fixing time are still abnormal after the reform. There is high volatility in pre- and post-fixing period. A reversal after the fixing period still exists at a level that could generate profits.

3.2 Liquidity and trading volume

Does the trading volume in the fixing window decrease after the reform?

Figure 2 shows the changes in fixing trading volume year by year. Each panel shows the average of daily trading volume around the fixing: (1) trading volume one minute before the fixing window, (2) trading volume during the fixing window, (3) trading volume one minute after the fixing window. Before the reform, the window is between 15:59:30 and 16:00:30. After the reform, the window is between 15:57:30 and 16:02:30.

For projecting the demand for fixing trades, we calculate an “excess” fixing trading volume. The excess volume is the excess of trading volume to the average one-minute volume between 15:00:00 and 17:00:00. The average is taken monthly to control for low-frequency trend and the monthly seasonality. After the reform, the average of the five-minute volume is subtracted, adjusting for the extension of the window. The excess of fixing trade volume to normal times is, averaged across years, 289 units for EUR/USD and 207 units for USD/JPY.

The figure shows that the trading volume in the fixing does not necessarily decrease even after the reform. Thus, the reform does not discourage nor encourage the fixing trades significantly.

Changes in the intra-fixing liquidity and trading volume.

Figure 3 shows the pattern of trading volume and market depth around 4 pm London time. The depth is defined as the sums of the best ask and bid limit orders at the end of the four-second interval.[11] The trade volume is the sum of each four-second interval. Each variable is an average over sample days for the same (GMT) time interval.

For before and after the reform, we observe the increase in volume and depth in the fixing window, but their patterns are quite different. Before the reform, the trading volume gradually

[11] ICAP EBS changed the minimum price unit on March 11, 2011 and October 01, 2013. The first made the minimum price unit to be one-tenth (decimalization) of a pip (1/100 of a yen, in case of USD/JPY). The second change raised the price unit to a half pip. The size of limit orders that stays at each limit price is affected by this change, and an adjustment was necessary. We adjusted the best-quote volume by summing up to four best quotes (between the first and second changes) or by summing up to two best quotes (from the second change to the latest).

increases before the fixing window and reaches its first peak a few seconds after the beginning of fixing window. After the peak, the trade volume decreases toward the end, with another peak at 4 pm. The dynamics of depth follows the trading volume and the peak of depth also appears at 4 pm.

After the reform, the gradual increase in pre-fixing trading volume is not observed. The trading volume suddenly rises at the beginning of the window. Still, the trading volume slightly concentrates in the earlier period of the window, but far less evident than before. The trading volume spreads more evenly across the window. As before, there is a peak of trading volume at 4 pm. The depth also follows the dynamics of trading volume: it suddenly increases at the beginning of the window. The FSB report points out that this may be explained by a surge of manual trading.

Monthly changes in the patterns of trading volume in EUR/USD are shown in Figure 4. It is evident that the trading volume spreads over five-minute window after February 2015. Certain months, such as September 2015, show high trading volume several seconds around 4 pm. In the month when the total trading volume is particularly high, the volume tends to cluster around 4 pm rather than spreading across window. Again, it looks that the reform decreased the trading volume per second during the fixing. If the sum of the volume over the window is taken, however, the total trading volume has not changed a lot (Figure 2).

Another remarkable pattern in Figure 3 is that the ratio of trading volume in the first-half period of fixing (time between [start of fixing window -30sec,4 pm]) to that in the second-half (time between [4 pm, end of fixing window +30sec]). The ratio is presented in each panel. Before February 2015, the trading volume in the first-half is mostly 30% larger than that in the second-half. The ratio of the first-half volume to the second-half volume becomes much smaller after the reform, especially for a few months after the reform. Recently, the trading volume in the first-half tends to increase. The average of the ratio after the reform is 1.24 which is smaller than 1.42 (p-value of t-test = 0.0062), the average of the ratio before the reform.

We consider the change in the volume pattern is important. As shown in next section, fixing traders (or banks) can reduce the transaction cost by taking a large position before the first-half of fixing window. This pre-hedging behavior has been criticized by the regulators, and it is discouraged after the London fixing scandal because it may represent the proprietary trades taking advantage of private information, or often called “front-running”. Theoretically speaking, the hump-shaped pattern of intra-fixing trading volume can be explained because of minimizing transaction costs even without proprietary trades. Observed patterns after the reform violate a cost-minimizing behavior of banks. Whether this is due to self-restraint by banks avoiding even an appearance of front-running. Alternatively, it may be a result of changed liquidity patterns around the fixing windows so that it may have become difficult to execute theoretically optimal trades.

In summary, surges in trading volumes are observed during the fixing periods after the reform as well as before. Per-minute trading volumes are less after the reform, but the total trading volume during the fixing window (1 minute before the reform, 5 minutes after the reform) stayed about the same after the reform. This is true even after taking the “excess” of the volume, i.e., trading volumes minus the average volumes. Most importantly, the pattern of trading volume in intra-fixing window changed. After the reform, the hump-shaped pattern of trading volume, a potential connection with the pre-hedging trades, disappeared.

3.3 Predictability after the reform

As mentioned earlier, the fixing “scandal,” which resulted in large fines on banks, made the banks extremely conservative and careful not to give any appearance of using private information about customer orders. Suppose that each dealer decided to pass customer orders for fixing prices on to the interbank market in equal batches over five minutes of the fixing window, which is consistent with observations of the volume pattern in the fixing window after the reform. This order pattern avoids any suspicion of taking advantage of private information about customer orders. Moreover, the average execution prices would turn out to be close to the fixing price that is the sampled median of transactions during the 5-minute window. So, for example, customer orders of 300 units (one unit = 1 million dollars in JPY/USD) are divided into 300 x 1 unit, and 1 unit is executed in every second.[12] If every bank behaves like this, after several seconds, bank orders for the rest of the fixing window become predictable by others (proprietary traders and professional trading communities). By spreading orders evenly over the fixing window, a bank reveals private information and, collectively, banks reveal market order imbalances. They become quite vulnerable to strategic nonbank traders.

Hence, a testable hypothesis is whether the order flows in the beginning of the fixing window can predict the price movements in the rest of the window. We examined this by taking the average of the price path conditional to the magnitude of order flows in the first 30 seconds from 15:57:30 to 15:58:00. Put differently, we measured the persistence of the price impact that is ignited by the order flows in the first 30 seconds of the window. When the market is efficient, the 30-second order flow does not have an impact on the future price movement.

Banks’ behavior may not have changed on the exact day of the reform, but, as Figure 4 shows, there exist clear structural changes in the trading volume pattern on the date of the reform. For this reason, we decided to use the sample from February 15, 2015 to June 30, 2016 (the total sample size is 359) for examining its predictability. We first calculated the sum of order flows in the first 30 seconds of the five-minute fixing window. Conditional on the magnitude of the order flows, we calculated the average of the price path (Figure 5) and the price change in the rest of the fixing window (Table 4). The price is the mid-price obtained from the limit order book data. In Table 4, we

[12] To be precise, the fixing window is defined as 61 seconds around 3:59:00 through 4:01:00 before the reform and 301 seconds round 3:57:30 through 4:02:30. However, it is approximated as 300 seconds for the simplicity of exposition.

showed $(\mathrm{P}_{16:02:30} - \mathrm{P}_{15:58}) \times sign(order\ flows) - bid\&ask\ spread_{16:02:30}$. If this value is positive, it indicates that the predictability can be profitable over the transaction costs.

The conditional average price path shows that, for some currency pairs such as EUR/JPY and EUR/USD, the price keeps moving toward the direction of the order flows in the first 30 seconds. This tendency is more pronounced in the sample of days with extreme imbalances of order flows.

So the finding here is consistent with a hypothesis that, after the reform, banks attempted to avoid further legal risk related to fixing transactions by spreading orders evenly and executing automatically over the fixing window through the usage of simple algorithm trading (Financial Stability Board (2015)). This produced a predictable price path during the fixing window after an initial segment of time, say 30 seconds, because all subsequent trades submitted by a bank would be a repeat of the initial segment. Market participants other than banks, such as proprietary human traders and algorithm traders in the professional trading community, can exploit this predictability and come up with a trading strategy to earn extra profits.

However, this kind of inefficiency cannot last long. Banks must have modified the order distribution patterns without jeopardizing the appearance of taking advantage of private information to their advantage. In a sense they must have corrected patterns so that they would become neutral rather than sure losses from trades in the fixing window. They could introduce a bit of randomization. We do not know how banks corrected the order pattern or how long it took for them to change the pattern. So, we conducted a crude test by splitting the after-the-reform samples into half and showed the results of the first half vs. those of the second half.

Table 4 shows the subsample analysis for the predictability. The sample is divided into two; between February 15, 2015 and October 29, 2015, and between November 1, 2015 and June 30, 2016. Each has 179 business days as a sample size. As observed in Figure 5, the predictability is high for the first half. For example, EUR/USD at the sample above is in the 90th percentile of positive order flow, the price change is 4.52 pips on average. For the samples above the 90th and 95th percentiles, as well as the samples below the tenth and fifth percentiles, most of the statistics are positive, indicating predictability. However, the large part of the predictability is lost in the second-half sample; the statistics are negative. This implies that such a chance of profitability had not continued for long. A question is how long the profit opportunities lasted.

We conjecture that the predictability of the price movement in the fixing window existed right after the reform of February 2015, but diminished gradually, as banks figured out how not to be taken advantage by others. In order to verify this conjecture, we conducted a rolling regression. In order to show this, we implemented a rolling regression analysis:

$$P_{16:02:30,d} - P_{15:58:00,d} = \lambda oib_d + \epsilon_d, \qquad d = \text{Feb/15/2015 to June/30/2016 (359 days).}$$

The dependent variable is the price change from 30 seconds after the fixing window starts to the end of the window. The independent variable is the sum of order flows in the first 30 seconds. The rolling window spans for 40 days, with rolling starting on February 15, 2015. We show the time-series change in the coefficients λ with their one standard error bars in Figure 6. The positive and statistically significant coefficient implies that the order flows have predictive power for the rest of the fixing window. Market participants other than banks could exploit this information and come up with the profitable trading strategy, and they probably did. In the figure, we show the results for three currency pairs (EUR/JPY, EUR/USD, USD/JPY), whose EBS transaction volumes are high. The profitability lasted for about 8 months for the EUR/JPY currency pair, for about 2 month for EUR/USD, and for about 3 months in the USD/JPY market.

In sum, the evidence is consistent with the hypothesis that the reform made banks behave naively to avoid the appearance of collusion or of the use of private information about customer fixing orders; moreover, that behavior must have taken advantage of by non-bank participants. Banks corrected their behavior, so that predictability disappeared after less than a year.

4 Analysis on the cost and risk of fixing trades[13]

The extension of the fixing window from 1 minute to 5 minutes was implemented to increase the cost of manipulation. It also helps to reduce execution costs because banks can split a big customer order into smaller parts to execute it slowly to avoid price impacts. However, after the reform, banks are subject to more risk that comes from the random-walk component of the price fluctuations. In this section, we calibrate the execution cost and associated risks of fixing trading by using the model of the optimal execution strategy (Obizhaeva and Wang (2013)).

The Model

We consider a strategy of sequential trade sizes $\{x_n\}_{n=1}^{N}$ that solves the following optimization problem:

$$\min_{\{x_0,\cdots,x_N\}} E_0\left[C_{t_N}\right]$$

$$s.t.\ C_{t_N} = \sum_{n=0}^{N}\left[A_{t_n} + \frac{x_n}{2q} - Ref\right]x_n,$$

$$A_{t_n} = F_{t_n} + \lambda\left(X_0 - X_{t_n}\right) + \frac{s}{2} + \sum_{i=0}^{n-1} x_i\left(\frac{1}{q} - \lambda\right)e^{-\rho\tau(n-i)},$$

$$0 \le x_n, \qquad 0 \le t_0, t_1, \cdots, t_N \le T. \qquad \cdots(1)$$

[13] The analysis in this section is based on our earlier letter journal article, Yamada and Ito (2016). However, the detail in data handling is slightly different: the parameters for calibration is estimated in equation (2).

A_{t_n} is an ask price just before nth trade x_n, and F_t is the fundamental value of the security without trade which follows a Brownian motion. Ref is the reference price to calculate the cost. We evaluate the reference price as either $A_0 - s/2$ (the mid-price) or a median of ask prices in a certain time interval (or the fixing rate), depending on the purpose of analysis. This change in the specification dramatically alters the solution. X_t is the remaining orders to be executed at time t, before trading at t. Thus $X_t = X_0 - \sum_{t_n<t} x_{t_n}$ and $X_{T+} = 0$ (or no remaining position after the last trade). λ, q, ρ, and s are the permanent price impact, limit order depth, resilience (or convergence speed to the fundamental value $F_{t_n} + \lambda\left(X_0 - X_{t_n}\right)$), and bid-ask spread. The transaction price at t_n is $A_{t_n} + x_{t_n}/q$ and the transaction cost is $\left[A_{t_n} + x_n/(2q) - Ref\right]x_n$. The trade times are fixed at $t_n = n\tau,\ \tau \equiv T/N$.

This problem takes the form of linear quadratic regulators, and Obizhaeva and Wang (2013) provides the closed-form solution with the assumption of a constant depth and bid-ask spread. Our specification differs at least in two; the time-varying depth and bid-ask spread and the Ref set as the fixing rate. The time-varying liquidities make the traders to trade more when the liquidity is many. When Ref is the median of the transaction prices, for replicating the fixing transaction, Ref can be a function of trading volume $\{x_n\}_{n=1}^{N}$. When Ref is given as the price at the beginning of the trading, traders cannot affect it. Thus, the trading volume patterns, costs, and risks become different for each specification. The reform and the legal pressure potentially discourage banks to take the trades influencing Ref itself. These modifications make the calibration more realistic and comparable to the observed data, but the analytical solution becomes more difficult to derive.

For calibrating the model, each structural parameter is estimated from the data. The depth parameter q is estimated from the limit order book information. This is done through the regression of the distance of the nth limit ask price A_t^n from the best ask price A_t (i.e., $A_t^n - A_t^1, n = 2, \cdots N$) on the cumulative limit order volumes up to $n-1$th steps (i.e., $\sum_{k=1}^{n-1} Volume_t^k$). The bid-ask spread is also obtained from the order book information. While Obizhaeva and Wang (2013) assumed a constant depth and bid-ask spread, we allow depth and bid-ask spread to be time-varying.

Throughout this calibration, we assume that the interval of time is three seconds. The time-stamp of the price is set to the nearest three-second grid. The order flows are the sum during each interval. The If there is no observation within any three seconds in data, we interpolate the observation: the state variables (such as price, depth, and bid-ask spread) are replaced with the last observation, and the flow variables (such as trading volume and order flows) are replaced with zero.

The permanent price impact λ and resilience ρ are estimated from the following regression of mid-price return r_t on order flows v_t:[14]

[14] In this specification, different from previous version of this paper (Yamada and Ito (2016)), contemporaneous order flows rather than lagged order flows are used as an independent variable. When considering the data construction, the specification is essentially identical.

$$r_t \equiv \Delta P_t = \lambda v_t + \sum_{k=1}^{K} \beta_k \Delta v_{t-k} + \epsilon_t \quad \cdots (2)$$

This equation corresponds to the difference of the transition equation of A_t in the minimization problem (1). P_t is the observed mid-price and ϵ_t is the unobserved random-walk component of fundamentals F_t. Associated with the estimates of depth q and permanent price impact λ, the estimated coefficients $\{\beta_i\}$ give the inference on the resilience ρ. In practice, we regress $\{log\ (\beta_k/(1/\bar{\hat{q}} - \hat{\lambda})), k = 1,2,\cdots,n\}$ on the distance of lag $k = \{1,2,\cdots,\mathrm{n}\}$. The regression coefficient yields the estimate of $-\rho$. The estimation of parameters is executed for the daily basis.

The averages of daily estimates of $\{\hat{\lambda}, \hat{\rho}\}$, $\{\hat{q}_i\}$, the assumption of window-length T (sec), and the number of trades $N = T(sec)/3(sec)$ are used to calibrate the limit order book dynamics. Since we assume that the depth and the bid-ask spread are time-varying, the minimization problem is solved numerically.[15] We assume $x_n \leq X_0$; at each time, traders cannot trade more than the customer orders. In case of $1/\mathrm{q} - \lambda$ being negative, the solution of the minimization problem becomes unbounded. This assumption avoids the problem. Since we also assume $x_n \geq 0$, traders cannot have position more than X_0, or they do not have a proprietary position.

The pre-calibration estimates are shown in Table 5. We examine the *trading* window of $\mathrm{T} = \{60, 120, \cdots, 600\}$.[16] The depth (average over the window) is presented as its inverse, meaning the changes in pips on 1 unit of trade.[17]

Calibration and discussion of the model prediction

The estimates above are translated into a total transaction cost. As an assumption, X_0 is normalized to 100. The reference price Ref is set as either $A_0 - s_0/2$ (first mid-quote) or the fixing rate, which is approximated by the average of the ask price during the 60-second window (or a 300-second window after the reform).

The settings for the reference price strongly affect the incentive for the traders. In the case of the first mid-quote as the reference price, which is a typical optimal execution problem, traders are assumed not to employ pre-hedging. In the case of the fixing rate as the reference price, the reference price becomes a function of $\{x_n\}$. Thus, traders can use pre-hedge.[18] The calibrated optimal strategy

[15] Matlab function "fmincon" is used to derive the numerical solution.

[16] It should be reminded that we change the length of trading window, not the fixing window. Traders are free to change the trading length but we set the length as given.

[17] The "pip" represents the minimum price unit of the currency rate before the decimalization occurred. For EUR/USD, it is one cent, and for USD/JPY, it is 1/100 yen. The "unit" of currency is one million in the EBS interbank market.

[18] In this paper, we use the term "pre-hedge" in the sense that traders can influence the average settlement price.

$\{x_n\}$ of $\mathrm{T} = 360$ is plotted in Figure 7. The price path following this strategy is presented in Figure 8.

First, when Ref is set as $\mathrm{A}_0 - \mathrm{s}_0/2$, the solution prescribes a large trade at the beginning of the trading and many small subsequent trades. Traders take advantage of resiliency by starting with the big-shot, which is a common recommendation from such a model. Depending on the bid-ask spread and the depth, the trade size during the fixing window substantially increases. The last trade is also slightly larger than the interim trades.

Second, more realistically, Ref is set as the fixing rate. The model predicts the existence of pre-hedging trades before the fixing window, and “banging-the-close” type of trading, or larger trades in the first half of the fixing window. In the second half of the fixing window, trading does not occur. The concentration of trades in the first half period causes a transitory impact on the prices and the return reversal after the end of trading. Because of the pre-hedging, the fixing rate increases, or the settlement price for banks with customers increases, and the total trading cost decreases compared to the first case.

In fact, the theoretical prediction of the second model (fixing price model) resembles the actual volume path observed in the data before the reform: the trade volume increases before the fixing period, reaches the highest at the beginning of the fixing window, and gradually decreases toward the end of the window (see Figure 3). In the post-reform period, the trading volume suddenly increases at the beginning of the window. The observed data look more like the first model where the reference price is set as $A_0 - s/2$. As presented in next analysis, this restriction can increase the transaction cost for fixing traders.

A price reversal after the end of the fixing window is observed in the case of fixing rate specification. If traders do not aim to affect prices, they continue trading even after the fixing and the price reversal does not appear. The price reversal occurs because of the resiliency of the price after the concentration of fixing trades. In the model by Osler and Turnbull (2017), to contrast, the traders holding proprietary position reverse the position after the fixing, and this generates the price reversal after the fixing. An important difference from the theoretical model by Osler and Turnbull (2017) is that we do not allow traders to take proprietary position nor taking the opposite position to the original customer orders. Also, Osler and Turnbull (2017) assumes there is no temporary price impact and therefore no resiliency. The information of the trade is immediately reflected into the price. Our result indicates that, if there is larger temporal price impact than the permanent price impact, the price reversal after the fix occurs even when the traders do not attempt the proprietary trading.

Cost and the risk of fixing trades

In the model, the traders are assumed to be risk-neutral and the random fluctuation of fundamentals is not a concern. In the reality, this risk can matter. We can evaluate the risk of trades by $\mathrm{Var}(C_{t_N})$. The only risk considered in the model is the random-walk component of the fundamental F_t and the variance can be simplified.

Let σ^2 be the variance of ΔF_t, $\mathrm{Var}(C_{t_N})$ reduces to $\sum_{n=0}^{N} \sigma^2 X_{t_n}^2$ when the reference price is $A_0 - s_0/2$. We evaluate σ^2 as the realized volatility of return of the data sample. When the reference price is the fixing rate, the expression of $\mathrm{Var}(C_{t_N})$ is atypical, and it is calculated from 100 simulation of the model. The simulation set the depth and bid-ask spread as given, and generates random paths of F_t. The average of the simulated cost of execution and its sample standard deviation, or the estimates of cost-risk trade-off $\left(E[C_{t_N}], Std(C_{t_N})\right)$, is presented in Table 6,

Fixing traders prefer less cost and less risk. Our focus is on how the reform, or the changes in fixing window-length, and the use of pre-hedge affect the cost-risk structure of fixing traders. The determination of optimal length of the fixing window is a different problem. The pattern of liquidity provision can be a function of the policy, which is given in our model. Although our research provides some insight into this problem, a complete discussion of optimal window-length is left to future research. In general, as the trading window extends, the transaction costs tend to become smaller and random-walk risk tends to be larger. If the fixing rate is used as the reference price, the cost can be negative, or fixing traders can make a profit.

The trading cost decreases when the pre-hedge is used. For EUR/USD within a 60-sec window before the reform, the difference amounts to 9.9 (not using pre-hedge) - 3.3 (using pre-hedge) = 6.6 (thousand dollars). Pre-hedging affects the reference price, which reduces the transaction costs. The risk is also reduced by using pre-hedge. If the banks cannot use pre-hedge after the reform, the rise of the trading cost is inevitable.

What is the difference before and after the reform? We investigate this for the specification that the reference price is $\mathrm{A}_0 - \mathrm{s}_0/2$. Since the results for EUR/USD and USD/JPY are similar, we comment on the overall results. In the calibration of the pre-reform case, the 60-second window had dominated the alternative window lengths in terms of the risk, while incurring the largest cost. After the reform, trading in the 300-second window, or the same length within the fixing window, incurs the cost at the same level as that of the 60-second trading before the reform but raises the risk dramatically. The traders cannot reduce the cost by splitting the trade less than the cost available before the reform. This is due to that the liquidity provision in the fixing window is not sufficiently high after the reform. Because of the insufficient liquidity provision, shorting the trading length makes the cost even higher.

If the banks must stop using pre-hedging after the reform and assume that they trade only in the fixing window, the increase of the cost for the exchange of 100 million dollars to 100 million euros. is estimated as \$13.1k – \$3.3k = 9.8 thousand dollars. This is approximately one basis point increase. The risk (or the standard deviation of the cost) increases by \$17.3k - \$5.7k = 11.6 thousand dollars.

5 Conclusion

This paper examined the liquidity and trading volume patterns around the London fixing time, which is at 4 pm, before and after the February 2015 reform. After the reform, the fixing time window was widened from 1 minute to 5 minutes. Its effects on the cost and risk of fixing traders have not been examined carefully in the literature. This is the first paper to find out the price and volume behavior and put them in the framework of a model for the problem of optimal execution that is used to evaluate the cost and risk. Our findings are summarized as follows.

First, the total cumulative surge in trading volumes during the fixing window did not change. They spread over 5 minutes, instead of 1 minute, after the reform. However, the surge is more evenly distributed in the window, as opposed to front-loaded previously. Second, some of the characteristics in price behaviors around the fixing windows did not change by the reform: the return reversal after the fix, the high volatility during the pre- and post-fixing period, and the end-of-month calendar effect. Third, after the reform, trading volumes prior to the fixing window became subdued. The trading volumes suddenly jumped at the beginning of the fixing window, and the trading volumes stayed at a constant level during the window, as opposed to a volume spike in the beginning of the window before the reform. These observations are evaluated in two analyses. Fourth, we conjecture that banks changed their behavior to avoid any appearance of taking advantage of private information from customer orders by placing a constant amount during the fixing window, which is consistent with the third observation. However, this behavior created profit opportunities for non-bank participants. Fifth, the calibration of an optimal execution model indicates that the extension of the window did not reduce the transaction cost, but increased the risk for fixing traders. The total liquidity during the fixing window did not increase despite the longer fixing window. The optimal execution model resulted in pre-hedging, which was discouraged after the reform.

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Table 1: Timeline of Foreign exchange benchmark scandal

Dates	Entities	Title/Summary
1994	WM/Reuters	Launch of London Forex benchmark.
12 June, 2013	Bloomberg	"Traders Said to Rig Currency Rates to Profit Off Clients"[19]
2013		Follow up by Financial Times and Wall Street Journal.
15 July, 2014	Financial Stability Board	"Foreign Exchange Benchmarks Consultative Document"[20]
30 September, 2014	Financial Stability Board	"Foreign Exchange Benchmarks Final report"[21]
September, 2014	IOSCO	"Review of the Implementation of IOSCO's Principles for Financial Benchmarks by WM in respect of the WM/Reuters 4.p.m Closing Spot Rate"[22]
11 November, 2014	US Office of the Comptroller of the Currency	Consent Order for Civil Money Penalty on Bank of America, Citigroup, and JPMorgan, for their deficiencies in its internal controls and had engaged in unsafe or unsound banking practices with respect to the oversight and governance of the Bank's FX Trading.[23]
12 November, 2014	Financial Conduct Authority	Impose fines totaling $1.7 billion on five banks for failing to control business practices in their G10 spot foreign exchange (FX) trading operations: Citibank N.A. $358 million, HSBC Bank Plc $343 million, JPMorgan Chase Bank N.A. $352 million, The Royal Bank of Scotland Plc $344 million and UBS AG $371 million.[24]
12 November, 2014	Commodity Futures Trading Commission	Impose fines over $1.4 billion in civil monetary penalties for attempted manipulation of Foreign exchange benchmark rates, specifically: $310 million each for Citibank and JPMorgan, $290 million each for RBS and UBS, and $275 million for HSBC.[25]
12 November, 2014	FINMA	"FINMA sanctions foreign exchange manipulation at UBS"[26]
15 February, 2015	WM/Reuter	Forex benchmark method change[27]
20 May, 2015	Commodity Futures Trading Commission	$400 Million Penalty to Settle CFTC Charges of Attempted Manipulation and False Reporting of Foreign Exchange Benchmark Rates[28]
1 October, 2015	Financial Stability Board	"Progress report on 2014 recommendations"[29]

19 http://www.bloomberg.com/news/2013-06-11/traders-said-to-rig-currency-rates-to-profit-off-clients.html

20 http://www.fsb.org/wp-content/uploads/r_140715.pdf

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25 http://www.cftc.gov/PressRoom/PressReleases/pr7056-14#PrRoWMBL

26 https://web.archive.org/web/20141115011002/http://www.finma.ch:80/e/aktuell/Pages/mm-ubs-devisenhandel-20141112.aspx

27 http://www.wmcompany.com/pdfs/WMReuters_Spot_Rate_Service_-_Methodology_Changes.pdf

28 http://www.cftc.gov/PressRoom/PressReleases/pr7181-15

29 http://www.fsb.org/wp-content/uploads/FX-Benchmarks-progress-report.pdf

Table 2: Trading profit around the fix

Before Reform

	Intra month						End of month					
	profit(bp)			SR			profit(bp)			SR		
holding time (min)	15	5	1	15	5	1	15	5	1	15	5	1
AUD/USD	-3.29	-2.63	-2.39	-4.68	-6.21	-11.2	-0.355	-0.257	-1.66	-0.47	-0.432	-5.54
EUR/GBP	-2.23	-2.13	-2.1	-5.16	-7.94	-15.8	-1.25	-1.23	-1.71	-2.18	-2.85	-7.97
EUR/JPY	-1.83	-1.66	-1.34	-2.57	-3.88	-6.7	-0.589	**1.17**	**0.115**	-0.751	**2.05**	**0.442**
EUR/USD	-1.06	-0.839	-0.597	-1.85	-2.45	-4.16	**0.617**	**0.827**	**0.171**	**0.974**	**1.75**	**0.827**
GBP/USD	-2.39	-1.89	-1.69	-4.5	-6.1	-11.6	-2.95	-2.6	-1.11	-4.32	-5.41	-5.81
USD/CAD	-2.12	-2.03	-2.17	-3.52	-5.4	-12.3	-2.18	-0.96	-1.6	-3.28	-1.76	-5.32
USD/CHF	-1.31	-1.26	-1.08	-2.02	-3.31	-6.14	**0.248**	-0.521	-0.569	**0.339**	-1.02	-2.32
USD/JPY	-0.883	-0.893	-0.776	-1.68	-2.75	-4.98	-0.904	**0.935**	**0.32**	-1.25	**2.46**	**1.48**

After Reform

	Intra month						End of month					
	profit(bp)			SR			profit(bp)			SR		
holding time (min)	15	5	1	15	5	1	15	5	1	15	5	1
AUD/USD	-1.58	-1.67	-2.52	-2.94	-5.73	-65.4	**4.26**	**0.939**	-2.69	**7.84**	**2.98**	-88.7
EUR/GBP	-2.29	-2.37	-2.72	-5.29	-9.43	-68.6	-2.76	**1.54**	-2.58	-5.38	**3.79**	-59.4
EUR/JPY	-1.31	-1.2	-1.89	-2.86	-4.77	-42.9	**2.91**	-0.0511	-2.04	**5.36**	-0.159	-61
EUR/USD	-0.519	-0.395	-0.861	-1.04	-1.43	-40	**1.21**	**1.32**	-1.02	**2.28**	**7.41**	-31.1
GBP/USD	-1.08	-1.72	-1.99	-2.68	-7.88	-49.1	**2.03**	**0.171**	-2.42	**2.2**	**0.348**	-16.8
USD/CAD	-2.47	-2.53	-2.62	-4.41	-8.3	-59.1	**3.31**	**2.12**	-2.74	**5.1**	**6.28**	-77.9
USD/CHF	-1.09	-1.72	-1.75	-2.11	-5.73	-38.3	**6.19**	-0.0809	-1.45	**14**	-0.209	-30.1
USD/JPY	-0.501	-0.556	-0.811	-1.4	-2.79	-36.9	**2.39**	**2.27**	-0.511	**6.99**	**8.48**	-28.6

This table shows the average profits (and Sharpe ratio) of investment of holding short (long) for X-minute if the 10-minute pre-fixing return is positive (negative). The investment starts at the last quotes during the fixing window: $\pm$30 seconds at 4 pm before Feb 15, 2015 or $\pm$150 seconds after Feb 15, 2015. The profit considers the transaction cost of spreads: when the investment starts from short (long), the triggering price is at the bid (ask) and liquidating price is at the ask (bid). The pre-fixing return is difference of the mid-price at 4:00:00 pm from the mid-price at 10-minute before the start of fixing window. The return defined as log-difference of prices. Sharpe ratio is defined as $\mathrm{ret}/\mathrm{std}(\mathrm{ret}) \times \sqrt{252}$. The positive profit is bolded.

Table 3: Tail probabilities for pre- and post-fix rate changes

Before Reform	Intra month						End of month					
	pre	pre	pre	post	post	post	pre	pre	pre	post	post	post
interval (min)	15	5	1	15	5	1	15	5	1	15	5	1
AUD/USD	0.0711	0.0804	0.125	0.0649	0.0644	0.0662	0.148	0.204	0.287	0.102	0.176	0.231
EUR/GBP	0.0769	0.072	0.121	0.0489	0.0565	0.0703	0.284	0.284	0.303	0.0826	0.156	0.211
EUR/JPY	0.0611	0.0637	0.1	0.0646	0.073	0.0677	0.176	0.241	0.352	0.13	0.167	0.222
EUR/USD	0.0618	0.0478	0.0872	0.0684	0.0776	0.0583	0.119	0.193	0.33	0.119	0.138	0.138
GBP/USD	0.0764	0.0671	0.115	0.0627	0.0653	0.0582	0.176	0.296	0.352	0.12	0.111	0.176
USD/CAD	0.113	0.119	0.186	0.0694	0.0992	0.0863	0.222	0.278	0.454	0.102	0.204	0.361
USD/CHF	0.0791	0.0836	0.107	0.0782	0.088	0.0685	0.148	0.25	0.361	0.148	0.157	0.167
USD/JPY	0.0782	0.0922	0.134	0.0654	0.0769	0.0742	0.204	0.306	0.454	0.157	0.139	0.222

After Reform	Intra month						End of month					
	pre	pre	pre	post	post	post	pre	pre	pre	post	post	post
interval (min)	15	5	1	15	5	1	15	5	1	15	5	1
AUD/USD	0.0647	0.118	0.147	0.0824	0.1	0.185	0.0625	0.0625	0.438	0.125	0.25	0.375
EUR/GBP	0.0472	0.0826	0.0944	0.0236	0.059	0.0796	0.294	0.176	0.118	0.0588	0.176	0.588
EUR/JPY	0.0437	0.0612	0.0758	0.0496	0.0671	0.0991	0.333	0.333	0.4	0.0667	0.133	0.2
EUR/USD	0.0549	0.0751	0.127	0.0549	0.0694	0.118	0.188	0.125	0.375	0.0625	0.125	0.25
GBP/USD	0.085	0.114	0.179	0.0469	0.0616	0.129	0.133	0.267	0.267	0.133	0.267	0.333
USD/CAD	0.115	0.147	0.191	0.115	0.118	0.188	0.0625	0.375	0.625	0.188	0.25	0.625
USD/CHF	0.0789	0.0936	0.14	0.0614	0.0965	0.135	0.4	0.333	0.2	0.133	0.267	0.333
USD/JPY	0.0636	0.101	0.0925	0.0434	0.0694	0.0838	0.333	0.267	0.267	0.0667	0.2	0.267

This table reports the frequency of days in which the absolute price changes in the window before and after the fix is larger than 95^{th} percentile from the distribution of the absolute price changes away from the fix. "Before the fix" window starts from X minutes before the fixing window starts. "After the fix" window ends at X minutes after the fixing window ends. The log-difference of mid-price is employed to calculate the return.

Table 4: Conditional changes in rates from 15:58:00 to 16:02:30

	before 20151030			after 20151030		
	>q75	>q90	>q95	>q75	>q90	>q95
AUD/USD	-1.59	-0.975	-0.375	-2.63	-1.8	-2.22
(std)	5.48	5.76	3.73	4.04	4.4	4.35
EUR/GBP	-1.72	-1.72	-0.929	-4.5	-4.5	-8.75
(std)	4.58	4.58	3.81	6.85	6.85	0
EUR/JPY	0.993	3.5	8.67	-4.54	-3.8	-2.89
(std)	9.21	9.24	9.92	10.6	8.82	10.5
EUR/USD	1.39	4.52	6.8	-1.28	-1.81	-2.14
(std)	5.43	4.52	5.75	6.87	8.68	4.23
GBP/USD	-2.85	0.542	0.542	-3.49	-3.9	-3.9
(std)	11.5	10.1	10.1	7.24	10.8	10.8
USD/CAD	-2.3	-2.12	-2.12	-5.28	-1.7	-1.7
(std)	9.34	10.1	10.1	8.72	9.86	9.86
USD/CHF	0.311	-0.405	9.68	-3.41	-8.21	-27
(std)	13	16.6	15.9	8.88	14	20.7
USD/JPY	-0.238	2.23	5.64	-3.45	-3.72	-3.95
(std)	6.44	7.86	8.71	5.95	7.04	8.15
	<q25	<q10	<q5	<q25	<q10	<q5
AUD/USD	0.0769	1.15	1.69	-1.84	-2	-1.35
(std)	6.04	7.84	5.81	4.42	4.76	5.93
EUR/GBP	-1.56	-1.56	1.69	-1.09	-1.09	1.38
(std)	3.29	3.29	2.59	3.45	3.45	2.3
EUR/JPY	-0.681	0.812	4.56	0.256	-0.269	1.17
(std)	8.24	7.12	7.94	6.76	9.08	10.3
EUR/USD	0.0213	1.74	1.81	-1.39	1.18	1.13
(std)	8.31	10.1	11.9	6.5	6.39	8.16
GBP/USD	-1.17	-1.12	-9.17	-3.04	-2.26	-2.58
(std)	11.3	13.4	9.4	13.2	14.9	9.75
USD/CAD	-1.38	-3.13	-3.13	0.382	-1.87	-1.87
(std)	7.25	9.37	9.37	10.3	7.24	7.24
USD/CHF	-3.78	-0.386	5.75	-4.38	-4.23	-2
(std)	9.97	7.71	4.6	5.53	6.38	5.36
USD/JPY	-0.131	-1.12	-1.56	0.165	1.66	0.694
(std)	4.69	4.93	5.06	5.81	6.57	8.53

This table shows the changes in forex rates (in pips) from 15:58:00 to 16:02:30 conditional on the magnitude of order flows during the first 30 seconds in the 4pm fixing window. The bid-ask spreads are already subtracted. The lower panel, the case of negative order flow, multiplies the changes in rates with -1 and then subtracts the bid-ask spreads. Thus, the positive values indicate a profitable predictability that overcome the spreads; the first 30 seconds predict the returns in the rest of the fixing window. The sample is from Feb 15, 2015 to June 30, 2016, and it is divided into two subsamples; each has 180 sample size.

Table 5: Pre-calibration estimates

EUR/USD, before Reform											
window	sec	60		180		300		420		540	
ρ		0.249	[0.0155]	0.315	[0.0127]	0.335	[0.00919]	0.338	[0.01]	0.334	[0.00869]
$\overline{1/\text{depth}}$	pip/unit	0.0403	[0.000826]	0.0484	[0.000748]	0.0519	[0.000677]	0.0539	[0.00068]	0.0553	[0.000652]
λ	pip/unit	0.0025	[0.000627]	0.00505	[0.000731]	0.00663	[0.000627]	0.00664	[0.000617]	0.00737	[0.00068]
$\bar{s}$	pip	0.857	[0.00929]	0.951	[0.00721]	0.97	[0.00686]	0.979	[0.00713]	0.983	[0.00666]
$\bar{\sigma}$	pip/3sec	0.23	[0.00504]	0.262	[0.0131]	0.242	[0.0113]	0.225	[0.00871]	0.214	[0.00781]
EUR/USD, after Reform											
window	sec	60		180		300		420		540	
ρ		0.17	[0.019]	0.233	[0.0199]	0.272	[0.0141]	0.283	[0.0177]	0.278	[0.0122]
$\overline{1/\text{depth}}$	pip/unit	0.0743	[0.00112]	0.0745	[0.00106]	0.0761	[0.00101]	0.0782	[0.000933]	0.0794	[0.000908]
λ	pip/unit	0.00927	[0.00182]	0.0125	[0.000949]	0.0135	[0.000744]	0.0142	[0.00086]	0.0137	[0.000831]
$\bar{s}$	pip	1	[0.00833]	1	[0.00734]	1	[0.00741]	1	[0.00705]	1	[0.00686]
$\bar{\sigma}$	pip/3sec	0.259	[0.00869]	0.32	[0.00871]	0.32	[0.00708]	0.324	[0.0101]	0.307	[0.0106]
USD/JPY before Reform											
window	sec	60		180		300		420		540	
ρ		0.278	[0.0146]	0.353	[0.0134]	0.385	[0.0178]	0.386	[0.0122]	0.38	[0.0114]
$\overline{1/\text{depth}}$	pip/unit	0.0411	[0.000957]	0.0535	[0.000918]	0.0593	[0.000916]	0.0627	[0.000929]	0.065	[0.000925]
λ	pip/unit	0.00211	[0.000597]	0.00424	[0.000811]	0.00531	[0.000748]	0.00528	[0.000535]	0.00616	[0.00056]
$\bar{s}$	pip	0.631	[0.00631]	0.873	[0.00656]	0.923	[0.00698]	0.945	[0.00718]	0.957	[0.00733]
$\bar{\sigma}$	pip/3sec	0.208	[0.00532]	0.25	[0.0155]	0.228	[0.0125]	0.21	[0.00858]	0.194	[0.00747]
USD/JPY after Reform											
window	sec	60		180		300		420		540	
ρ		0.162	[0.021]	0.234	[0.017]	0.252	[0.0139]	0.261	[0.0117]	0.27	[0.0114]
$\overline{1/\text{depth}}$	pip/unit	0.089	[0.00152]	0.0889	[0.00228]	0.09	[0.00181]	0.0917	[0.00153]	0.0928	[0.00141]
λ	pip/unit	0.00943	[0.00543]	0.0147	[0.0016]	0.0158	[0.0011]	0.0172	[0.00178]	0.0156	[0.0014]
$\bar{s}$	pip	1	[0.0107]	1	[0.0104]	1	[0.0099]	1	[0.00863]	1.01	[0.00817]
$\bar{\sigma}$	pip/3sec	0.203	[0.0272]	0.252	[0.0113]	0.253	[0.00848]	0.266	[0.0132]	0.248	[0.011]

This table shows the estimation of structural parameters for the calibration. The depth and bid-ask spread (s) are calculated from data. The average and $\text{standard deviation}/\sqrt{\#\text{obs}}$ is presented. Other parameters are estimated by the following regression of return r on order flow v: $r_t \equiv \Delta P_t = \lambda v_t + \sum_{i=1}^{K} \beta_i \Delta v_{t-i} + \epsilon_t$. λ and ρ are the permanent price impact and resilience (or convergence speed to the fundamental value). The regression is executed in daily basis, and the average of estimates and their $\text{standard deviation}/\sqrt{\#\text{obs}}$ is presented.

Table 6: Calibrated results of execution cost and risk

	EUR/USD					USD/JPY				
	Before RF			After RF		Before RF			After RF	
$Ref = A_0 - s/2$	window (sec)	cost ($1000)	risk	cost ($1000)	risk	window (sec)	cost ($1000)	risk	cost ($1000)	risk
	60	9.9	5.9	19.9	6.5	60	9.5	5.4	23.2	4.4
	120	8.5	9.5	15.1	11.4	120	8.4	10.5	17.8	8.6
	180	8.3	10.7	14.1	13.1	180	8.1	10.8	16.1	9.9
	240	8.1	12.9	13.6	14.9	240	7.7	14.8	15.2	11.3
	300	8.4	13.2	13.1	17.3	300	8	13.2	15	14.3
	360	8.3	12.9	13.9	18.6	360	7.9	14.8	15.2	17.4
	420	8.2	12.6	13	20.6	420	7.8	13.4	15.2	17.4
	480	8.5	16.1	12.4	21.8	480	7.9	15.7	14.6	15.7
	540	8.5	16.1	12.6	19.9	540	8.2	14.6	14.2	18.7
	600	8.7	15.4	13	19.8	600	8.1	15.5	14.6	19
	window (sec)	cost ($1000)	risk	cost ($1000)	risk	window (sec)	cost ($1000)	risk	cost ($1000)	risk
$Ref = fix$	window (sec)	cost ($1000)	risk	cost ($1000)	risk	window (sec)	cost ($1000)	risk	cost ($1000)	risk
	60	3.3	5.7	1.9	4	60	3.6	5.8	1.8	4.1
	120	3.1	10.2	2.9	8.3	120	3.5	8.1	2.9	6.1
	180	2.8	10	2.7	8.8	180	3.4	9.7	2.8	7.7
	240	2.6	9.7	2.3	9.1	240	3.4	11.6	2.6	9.9
	300	2	10.6	2.2	9.9	300	3.1	10.3	2.1	8.5
	360	1.9	11.4	1.2	11.9	360	3	11.8	1.4	10.9
	420	1.9	12.2	1.1	13.3	420	3	11.4	0.8	10.7
	480	1.6	12.8	1.3	11.4	480	2.8	11.6	0.8	9.5
	540	1.5	11.6	0.9	13.4	540	2.6	11.6	0.9	10.4
	600	1.2	10.9	0.3	14	600	2.6	11.6	0.3	10.8

This table shows the calibrated results for the execution cost and risk for EUR/USD and USD/JPY, before and after the reform (February 15, 2015). The reference price is $A_0 - s_0/2$ (top panel) or fixing rate (bottom panel). Execution of 100 units (or the exchange of 100 million currency) is assumed.

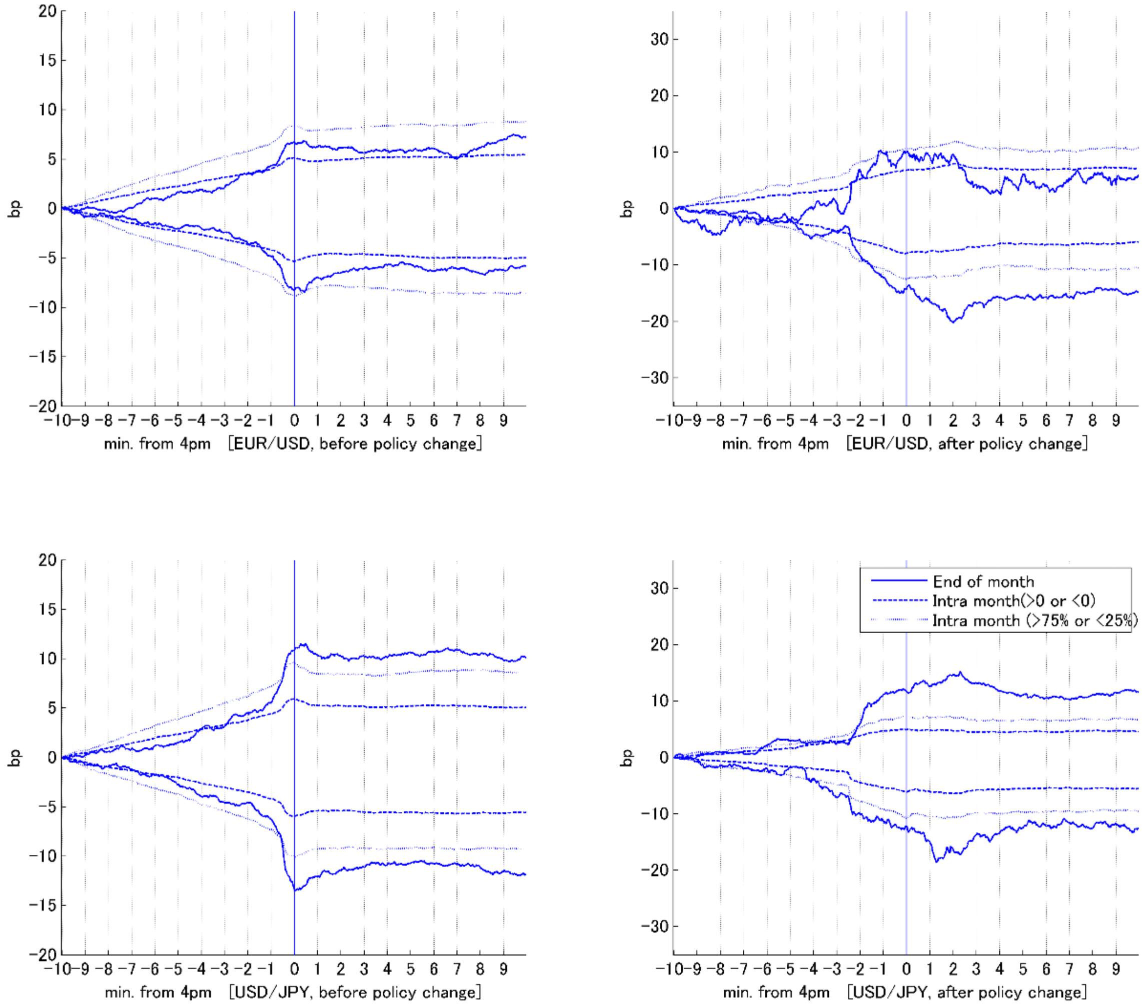

Figure 1: Average price path of EUR/USD and USD/JPY around the fix

This figure shows the average price pace of around the 4pm London fixing before (left column) and after (right column) the reform (February 15, 2015). The price is obtained from the quotes and is normalized by the mid-price at 15:50:00. The paths are conditional on (1) positive (or negative) pre-fix changes (over 10 minutes) at end of month (upper and lower solid); (2) positive and negative pre-fix changes on intra-month days (upper and lower dots); (3) pre-fix change above the 75th (or below the 25th) percentile for intra-month days (upper and lower dash).

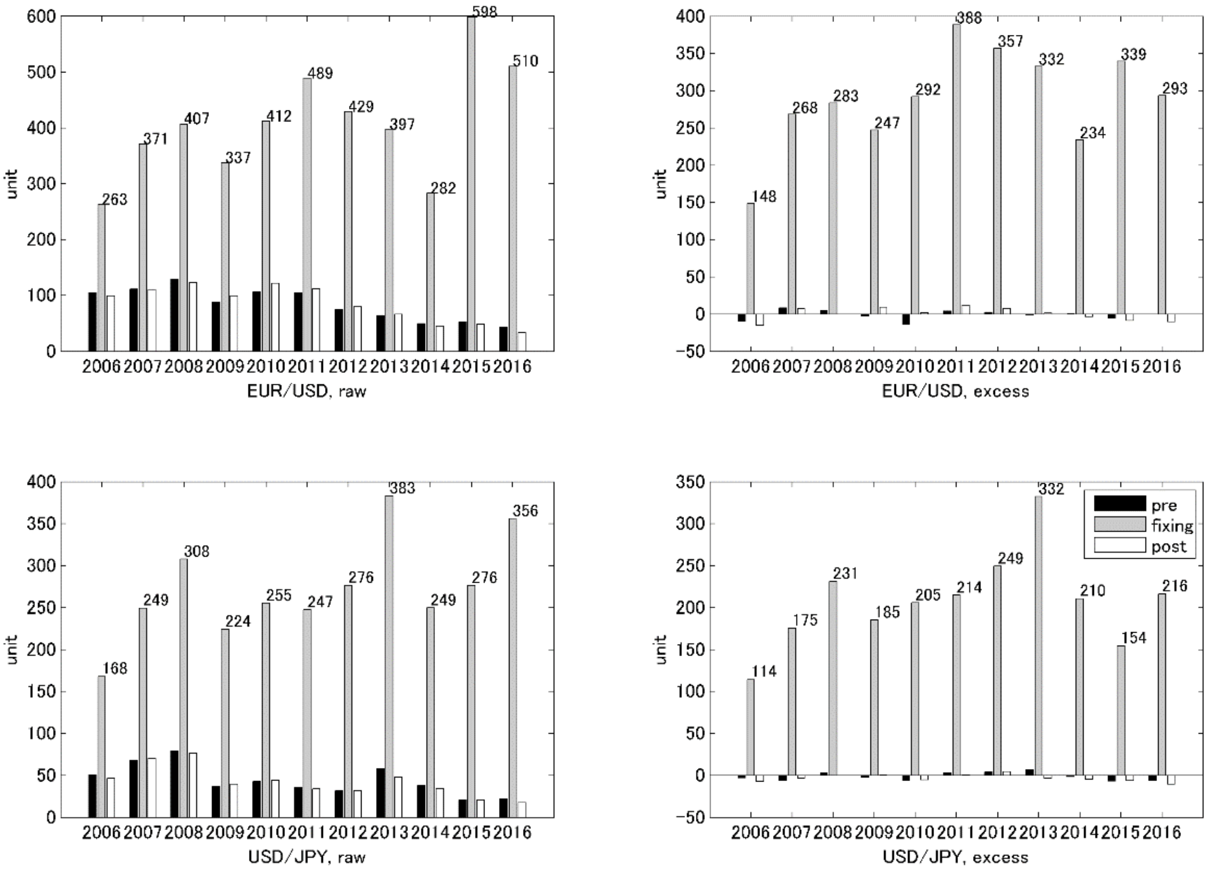

Figure 2: Total trading volume around the fix

This figure shows the total trading volume around the London fix. Raw (left column) and excess (right column) volumes are reported. Black, grey, white bars represent one-minute before the fixing window, during the fixing window, and one-minute after the fixing window. Excess volumes are defined by $\text{Fix trading volume} - \text{window length} \times \text{2hour average trading volume per minute}$.

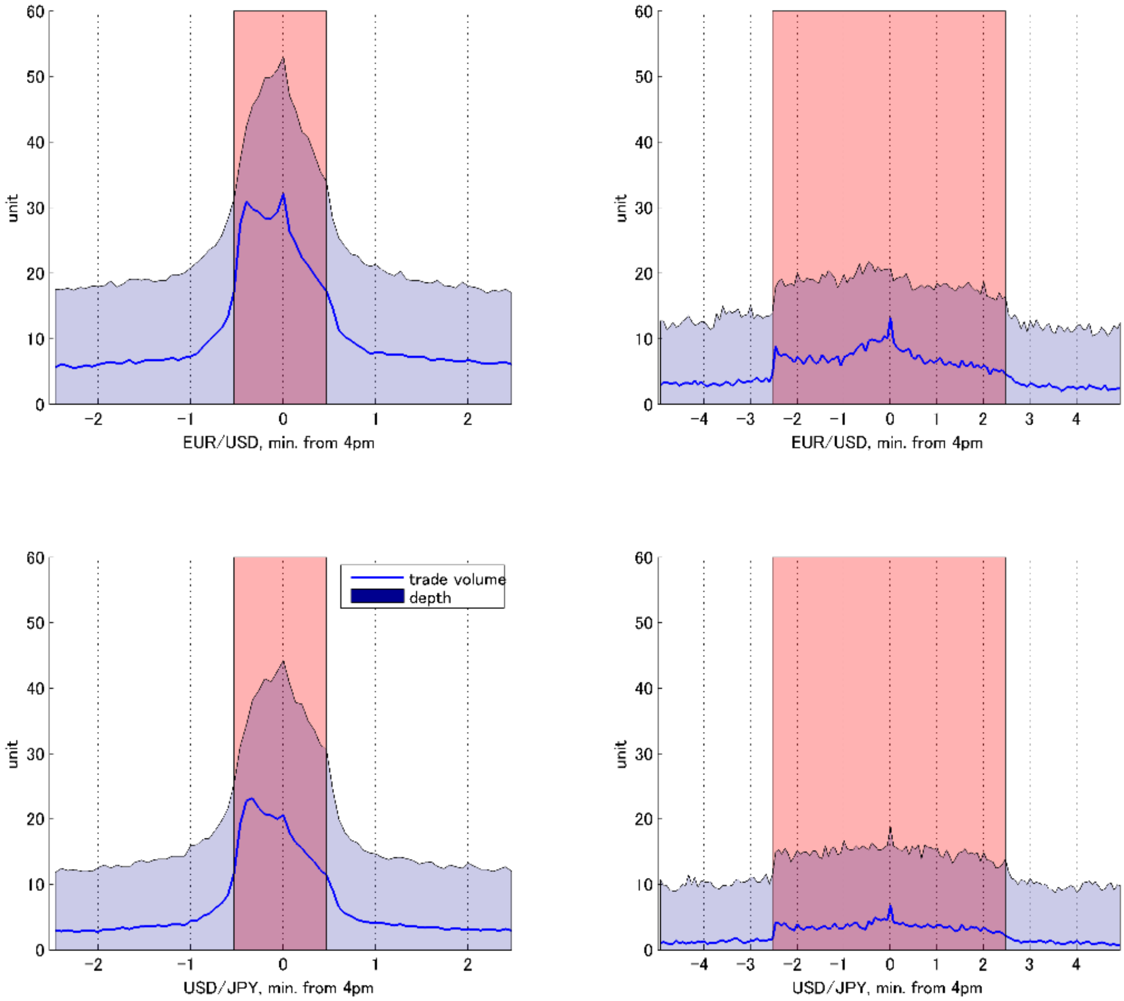

Figure 3: Average path of trading volume and depth around the fix

This figure shows the average path of trading volume and depth (up to four steps) around London fixing for EUR/USD and USD/JPY. Before (left columns) and After (right columns) the reform (February 15, 2015). The trading volume is the sum of every four seconds, and the depth is sampled at the last moment in each four seconds interval.

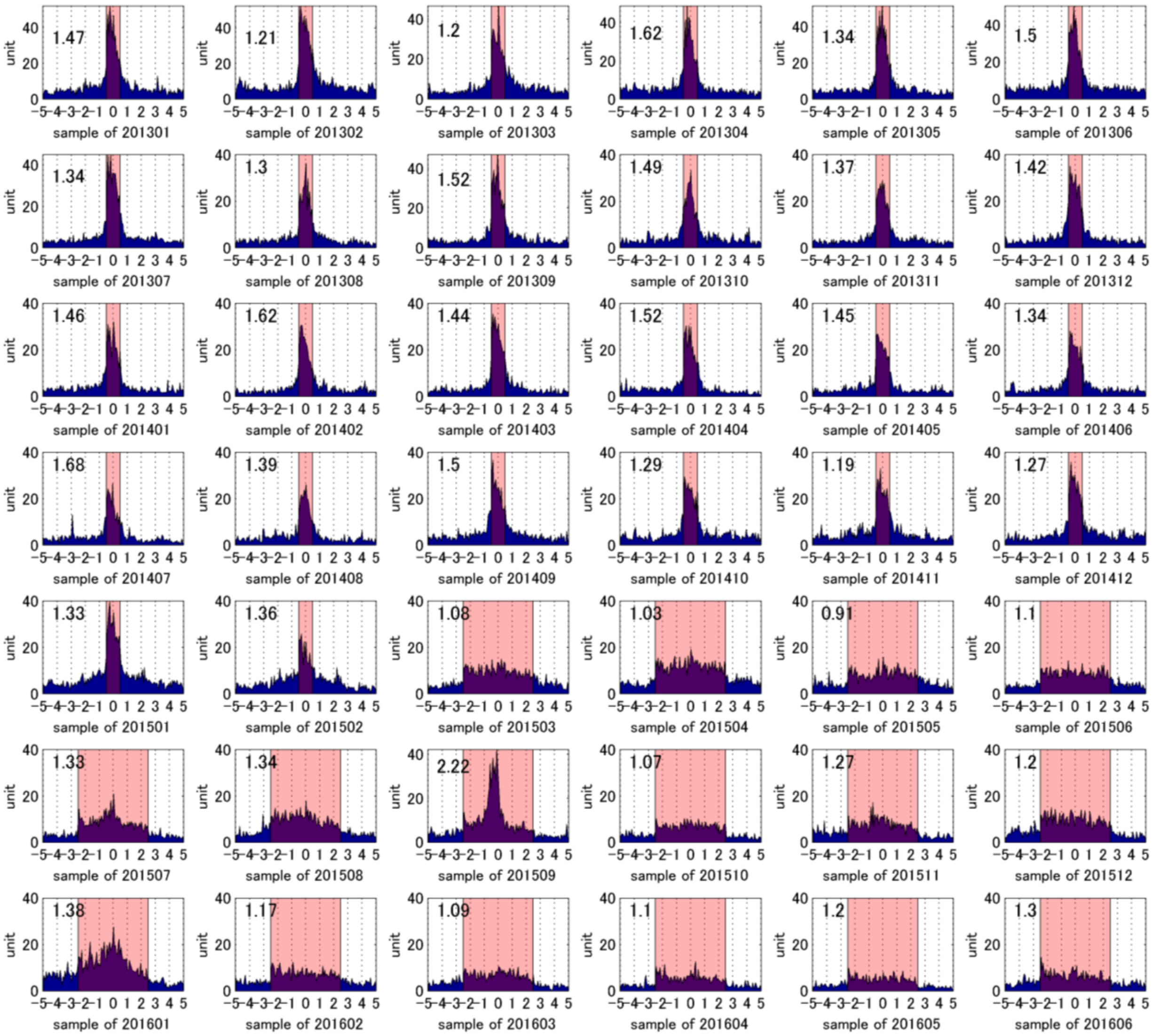

Figure 4: Monthly changes in the trading volume pattern around the fix

This figure shows the pattern of trading volume of EUR/USD around London fixing for each month (from January 2013 to June 2016). The figures in each panel is ratio of A to B, where A is the trading volume in the first-half period of fixing (time between [start of fixing window -30sec,4 pm]), and B is that in the second-half (time between [4 pm, end of fixing window +30sec]).

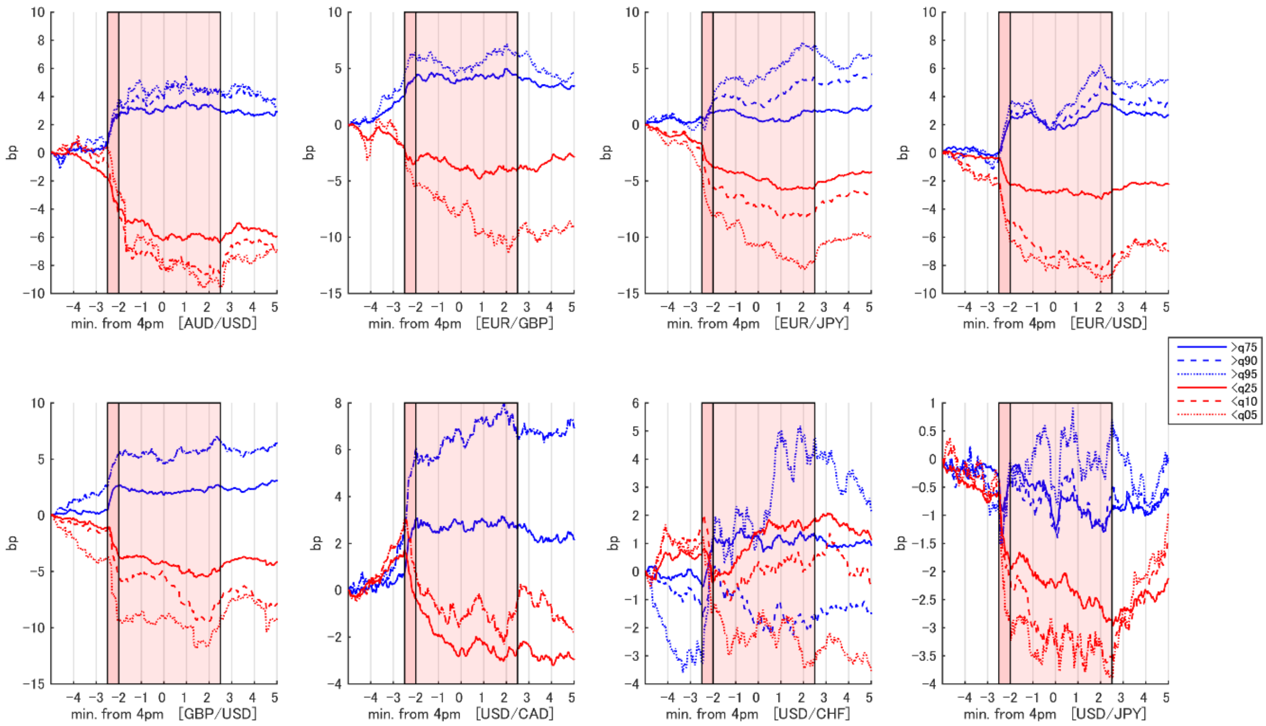

Figure 5: Average price path conditional on the order flows

This graph describes the average price path conditional on the sum of order flows in the first 30 seconds in the fixing window. For the conditions on the sum order flows, the sample above 75 percentiles, 90 percentiles, 95 percentiles, and the sample below 25 percentiles, 10 percentiles, and 5 percentiles are presented. The price is standardized at the one at 15:55:00. The sample is from February 15, 2015 to June 30, 2016.

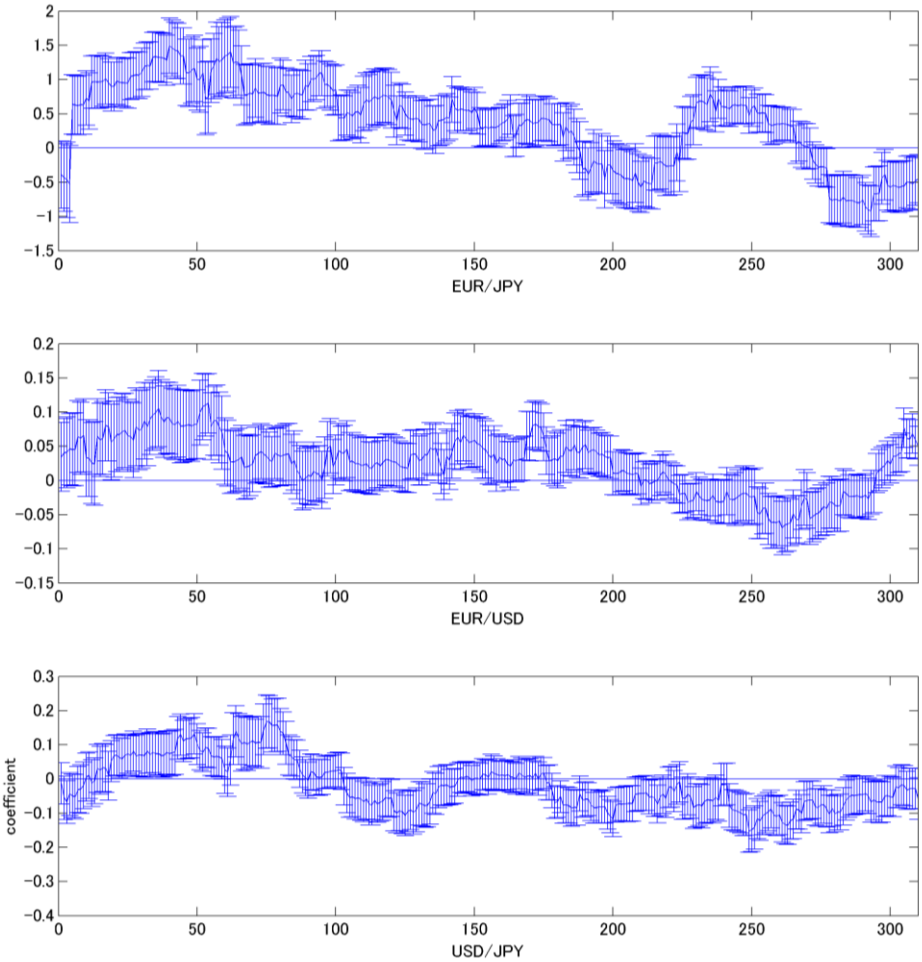

Figure 6: Rolling regression for predictability of fixing price movement

This figure shows the time-series changes of the predictability of fixing price movement. The horizontal axis is the day of the rolling regression window starts, counting from February 15, 2015. Each regression is: $P_{16:02:30,d} - P_{15:58:00,d} = \lambda oib_d + \epsilon_d$, where oib_d is the sum of order imbalance during the first 30 seconds in the 5-minutes fixing window at day d. We present the estimated λ with their 1 SE error bars. Each rolling window has 40 subsamples. The significant coefficients show the predictability of price movements in the rolling window specified by the dummy.

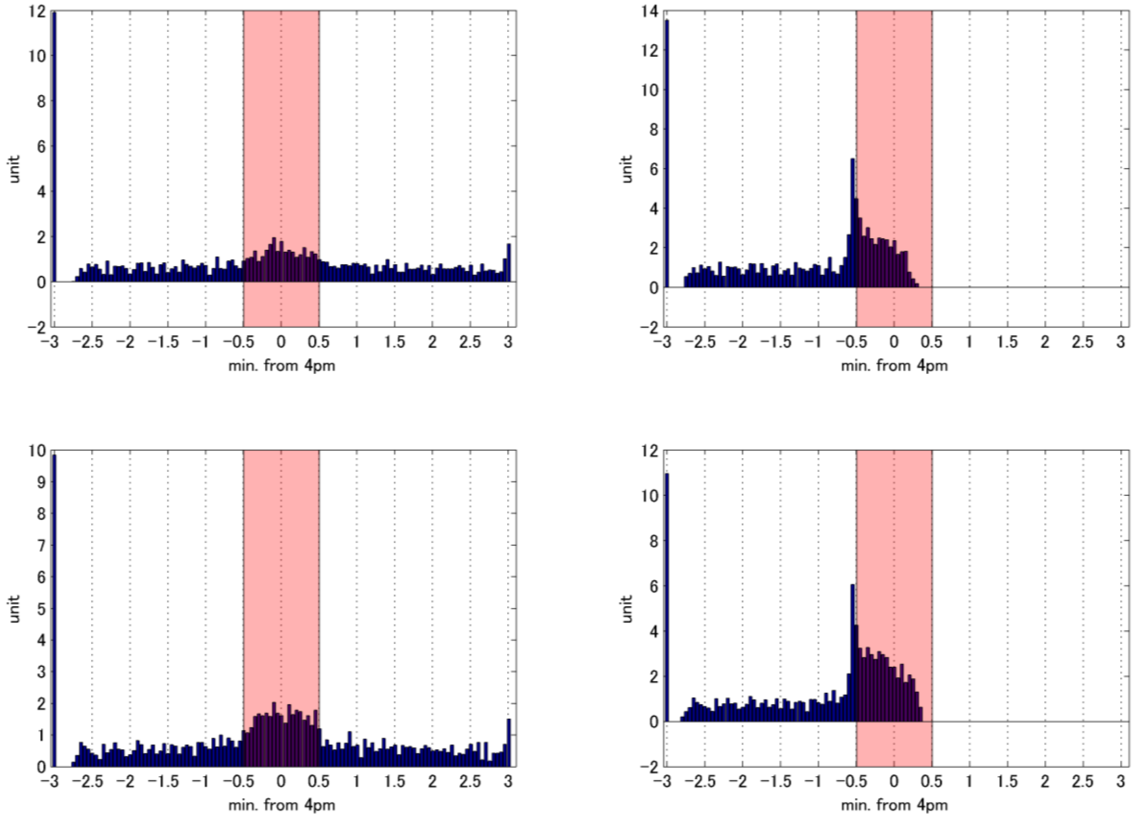

Figure 7: Optimal trading strategy

This figure shows the calibrated optimal execution strategy for EUR/USD (upper low) and USD/JPY (lower row). The reference price is $A_0 - s_0/2$ (left column) and A_{fix} (right column). The feeding parameters are the estimates from the sample from Oct 01, 2012 to Feb 14, 2015. Execution of 100 units (or the exchange of 100 million currency) is assumed.

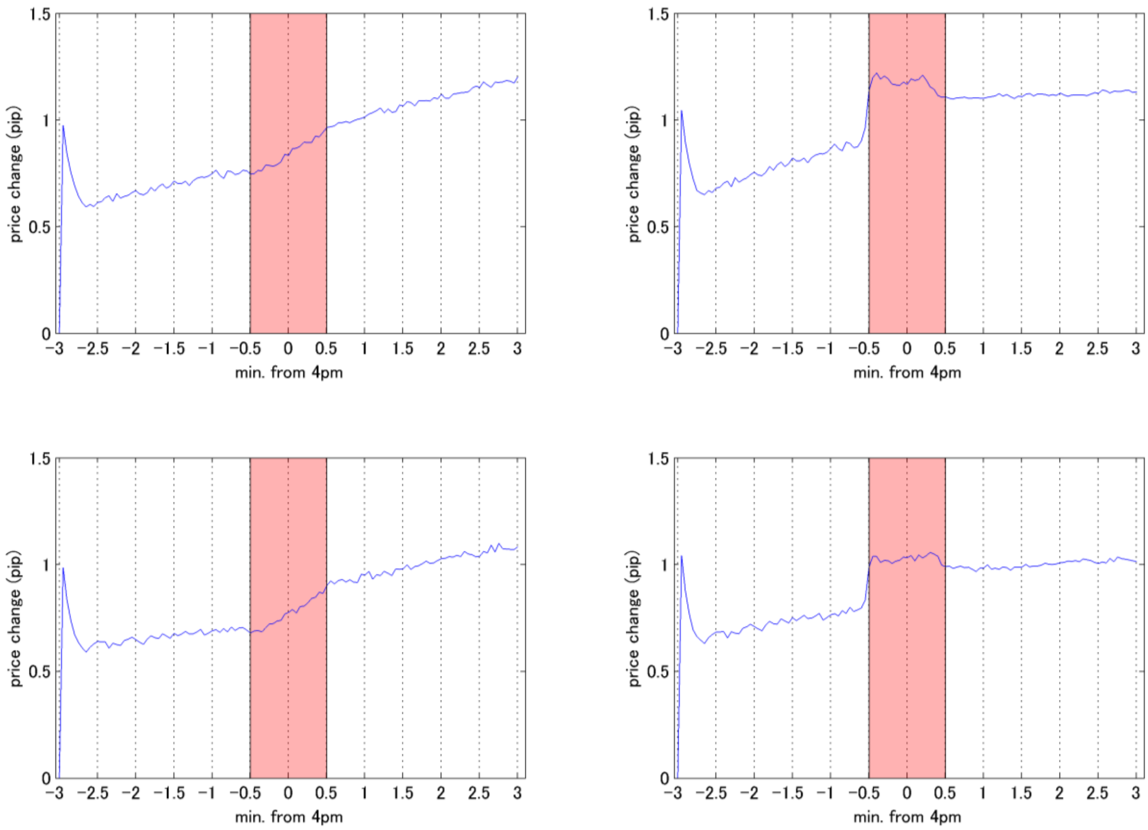

Figure 8: Calibrated price path

This figure shows the calibrated price paths generated by the optimal execution strategy. EUR/USD (upper low) and USD/JPY (lower row). The reference price is $A_0 - s_0/2$ (left column) and A_{fix} (right column). The feeding parameters are the estimates from the sample from Oct 01, 2012 to Feb 14, 2015. Execution of 100 units (or the exchange of 100 million currency) is assumed. The random walk component is suppressed.