

Internet Appendix for

“Low-Latency Trading and Price Discovery: Evidence from the Tokyo Stock Exchange in the Pre-Opening and Opening Periods”

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IA 1. Order flow in the pre-opening period

As explained in Section 4 of the paper, the pre-market-opening period of the TSE starts at 8 am. All member firms begin to send orders from their customers' and their own accounts to the exchange. The results from the three different trading-speed groups are reported in Figure IA 1.1, Panel A. The green line represents orders from FAST traders, who play a dominant role during the whole pre-opening phase. FAST traders submit 50.5% of the total number of orders in the pre-opening period, with MODERATE and SLOW traders submitting 42.5% and 7.0%, respectively. In the first 10 minutes of the pre-opening period, 73.7% of the total number of orders of the entire pre-opening period are submitted. FAST traders submit 36.0% out of their 50.5% of orders in the first 10 minutes, MODERATE and SLOW traders submit 32.8% and 5.0%, respectively. The order submission intensity slows down after the first 10 minutes, and is reactivated 10 minutes before the official opening time. The high level of order submissions in the first 10 minutes partly reflects the accumulation of orders overnight. Early investors also have a desire to lead price formation for the opening call auction. Figure IA 1.1, Panel B, shows the order flow for the four different inventory groups. The majority of the order flow comes from trades with small and medium inventories. Figure IA 1.1, Panels C, D, and E present the pattern of order submission activity for the FAST, MODERATE, and SLOW traders during the pre-opening period, classified according to level of inventory for each group. They clearly show a peak at the very beginning of the period for traders with SMALL and MEDIUM levels of inventory, and another very close to the opening time for FAST/SMALL (HFTs) traders, vastly exceeding the number of orders

submitted by slower traders. FAST traders submit 7.5% of the total number of orders in the last 10 minutes of the pre-opening period, and MODERATE and SLOW traders submit 4.4% and 1.0%, respectively. Traders with a LARGE inventory and those in the NOTRADE group submit most of their orders at 8 am. One of the reasons traders submit more orders at 8 am is to ensure a higher probability of execution of their orders due to the time-priority-based allocation most brokers employ, as explained in Section 4.

Figure IA 1.2 Panel A shows the new order submissions and cancellations as a percentage of all orders submitted by FAST, MODERATE, and SLOW traders, in the last 10 minutes of the pre-opening period. While the magnitude of the order submission differs (as the scale of the y -axis differs between FAST, MODERATE, and SLOW traders), the pattern is quite similar for all three groups. Traders accentuate their pattern of order submission during the last three minutes of the pre-opening period. A rise in order cancellations (indicated by the black line) happens suddenly, one second before 9 am, for all trader groups. For instance, the percentage of cancellation messages increases from less than 0.1% to 0.9% (of the total number of orders in the pre-opening period) per second for FAST traders, and from less than 0.01% to around 0.25% for MODERATE-speed traders.

Figure IA 1.2 Panel B depicts order submissions and cancellations for the different inventory subgroups within the FAST group. It is interesting to note that cancellations from all trader groups reach their peak at the very last second. We investigate this in detail at the millisecond level and present the results in Figure IA 1.3 Panel A.

We confirm that the cancellations indeed occur less than one second before 9 am. As Figure IA 1.3 Panel B shows, the cancellation phenomenon starts at 500 milliseconds before 9 am and peaks at 130 milliseconds before 9 am. The peak is particularly pronounced for FAST traders and is not specifically related to inventory. The final action of limit price adjustment takes place just milliseconds before the opening time, which would not be possible in the absence of a low-latency trading environment.

Figure IA 1.1: Flow of total order submission in the pre-opening period

Figure IA 1.1 depicts the second-by-second order flow for 97 stocks from the TOPIX100 during the sample period of April-May 2013. The Tokyo Stock Exchange starts receiving orders at 8 am and starts the call auction at 9 am. The average percentage of the total number of orders is the total number of orders in each second divided by the total number of orders submitted during the whole pre-opening period (8:00:00.000 - 8:59:59.999). The Y-axis represents the percentage of the total number of new orders in the pre-opening period, and the X-axis represents the time in seconds between 8 am and 9 am. Panel A depicts the average percentage of the total number of orders by speed group, as defined in Table 2 using information about speed and inventory from the same day's continuous session, per second. Panels B, C, and D report, for each speed group, the average percentage of the total number of orders according to level of inventory, as defined in Table 2. Order flow data, with order IDs as well as virtual server IDs, are provided by the Tokyo Stock Exchange.

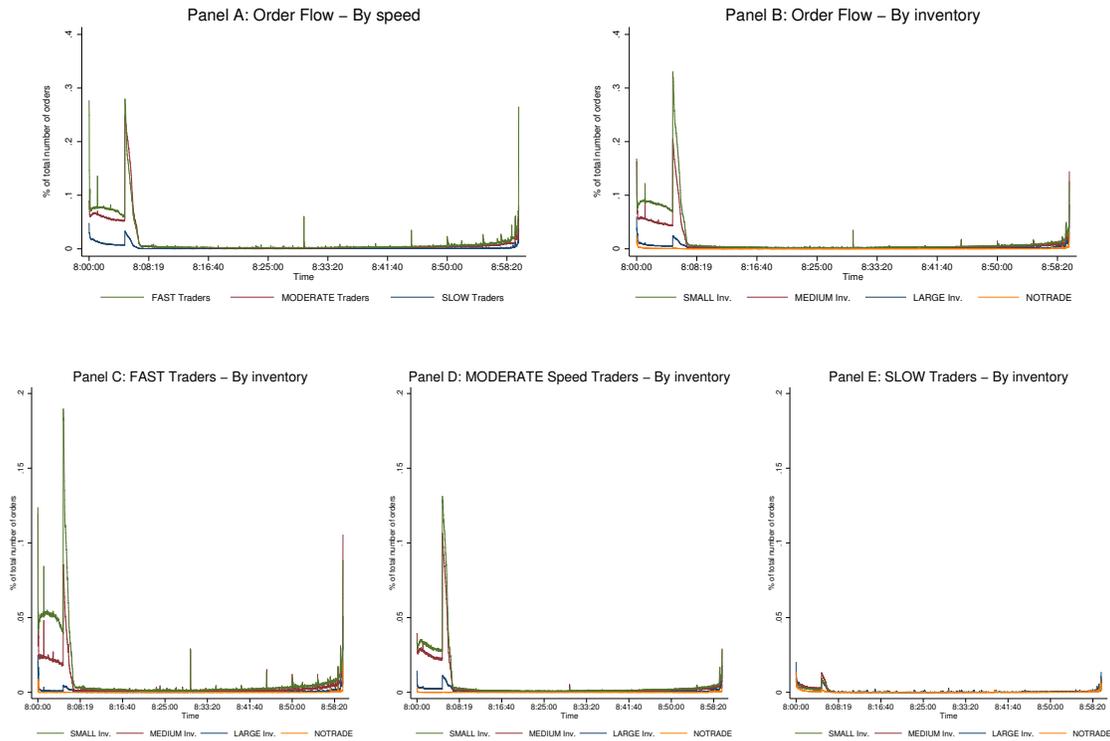
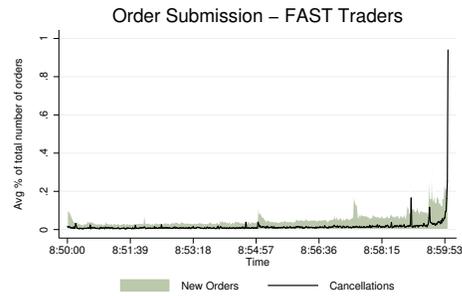


Figure IA 1.2: Flow of new orders and cancellations in the last 10 minutes of the pre-opening period

Figure IA 1.2 depicts the second-by-second new orders and cancellations for 97 stocks from the TOPIX100 during the sample period of April-May 2013. The Tokyo Stock Exchange starts receiving orders at 8 am and starts the call auction at 9 am. New orders and cancellations are measured as percentage of the total number of orders submitted in the last 10 minutes of the pre-opening period (8:50:00.000 - 8:59:59.999). The Y-axis represents the percentage of the total number of orders in the last 10 minutes of the pre-opening period, and the X-axis represents the time in seconds between 8:50 am and 9 am. Panel A depicts the average percentage of the total number of orders by speed group, as defined in Table 2 using information about speed and inventory from the same day's continuous session, during the sample period, per second. Panel B reports, for FAST traders, new orders and cancellations, according to the level of inventory. Order flow data, with order IDs as well as virtual server IDs, are provided by the Tokyo Stock Exchange.

Panel A - Submission of new orders and cancellations by speed category



Panel B - Submission of new orders and cancellations by FAST traders

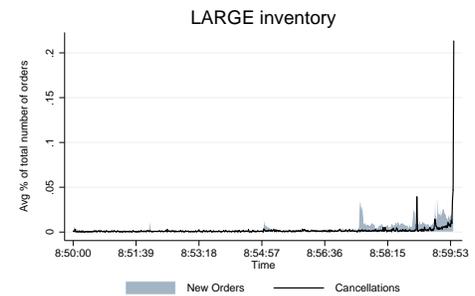
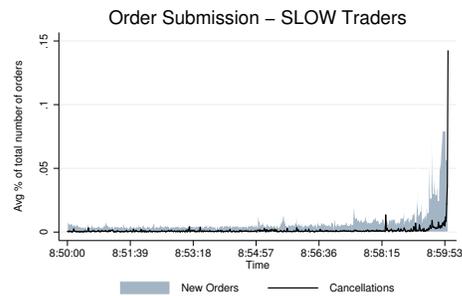
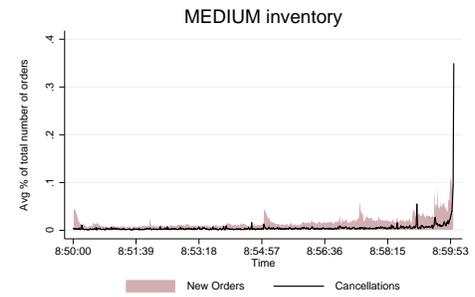
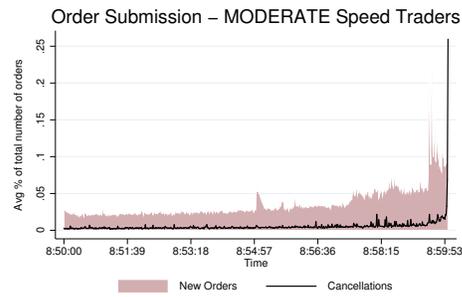
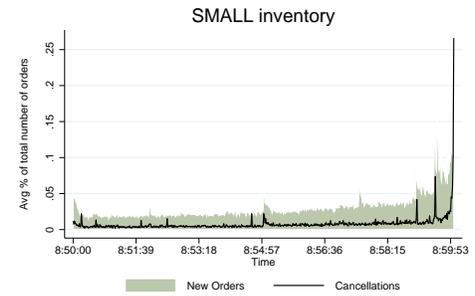
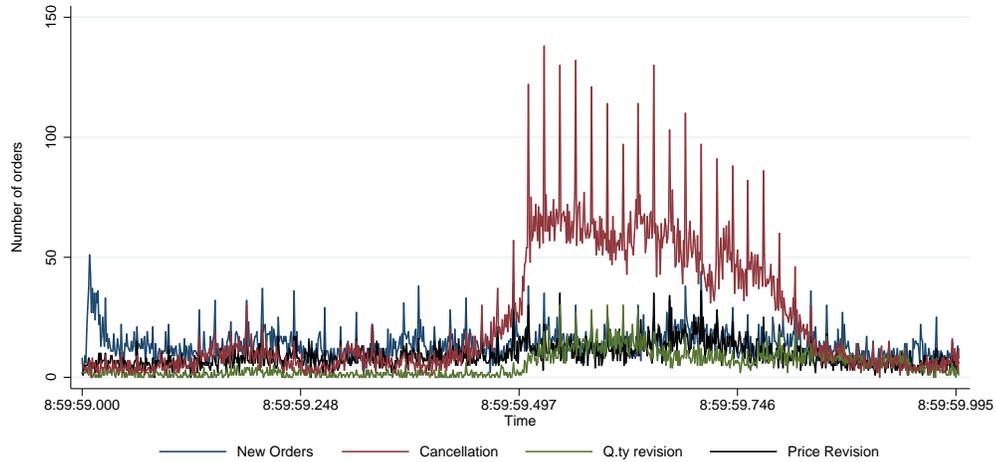


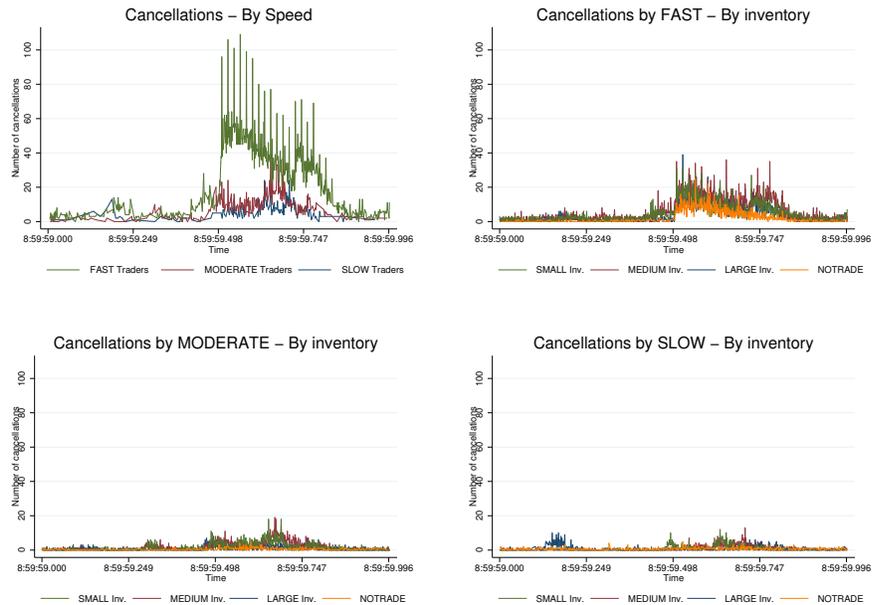
Figure IA 1.3: Order flow during the last second of the pre-opening period

Figure IA 1.3 shows four types of order submission activity: new orders (blue line), cancellations (red line), quantity revisions (green line), and price revisions (black line), in the last second of the pre-opening period (8:59:59.000 - 8:59:59.999) at the millisecond level, for all 97 stocks from the TOPIX100 during the sample period of April and May 2013. Panel A reports traders' order submission activity. Panel B focuses on cancellations, distinguishing between the different groups of traders. Order flow data, with order IDs as well as virtual server IDs, are provided by the Tokyo Stock Exchange.

Panel A - Order flow for all traders



Panel B - Cancellations by speed and inventory group



IA 2. Additional analysis for price discovery

Table IA 2.1: Weighted price discovery regression by stock-date

This table presents regression analysis by stock-date for the weighted price discovery contribution (WPC) during the pre-opening period and first 30-minutes of the continuous session (see equation XX) for 97 stocks from the TOPIX100 during the sample period of April-May 2013.. WPC is attributable to aggressive orders. Aggressive orders in the pre-opening period are defined as follows: (1) all market orders; (2) limit buy orders with a limit price greater than or equal to the prevailing best bid; (3) limit sell orders with a limit price less than or equal to the prevailing ask; (4) any orders submitted when best bid equals best ask (zero imbalance). Aggressive orders during continuous trading session are defined as orders that initiate the transaction (timestamp of the transaction should be equal to the timestamp of the new order entry or timestamp of the price revision): (1) new market orders; (2) limit-to-market orders; (3) new or revised buy (sell) limit orders with a limit price greater (smaller) than the best ask (bid) price ("Cross"); (4) new buy (sell) limit orders with a limit price equal to the best ask (bid) price ("Lock"). We divide all traders into 12 groups on a stock-day basis, as described in Table 2, using information about speed and inventory from the same day's continuous session. We also split traders into 3 categories: traders that are not active during pre-opening period (Non-Active), traders that participate during the pre-opening period, but do not trade at the opening call auction (Active-w/o-trade), and traders that participate during the pre-opening period and trade at the call auction (Active-w-trade). Order flow data, with order IDs as well as virtual server IDs, are provided by the Tokyo Stock Exchange.

Speed	Inventory	Pre-opening period			First 30-minutes of the continuous session			
		Active-w/o-Trade	Active-w-Trade	Total	Active-w/o-Trade	Active-w-Trade	Non-Active	Total
FAST	LARGE	-0.02***	-0.04***	-0.02***	-0.01	-0.02	-0.07	-0.02
	MEDIUM	-0.03***	-0.28***	-0.14***	-0.06***	-0.14*	-0.23***	-0.13***
	SMALL (HFTs)	-0.02***	-0.16***	-0.08***	-0.02	0.05	-0.49***	-0.14***
	NOTRADE	0.01*		0.02***				
MODERATE	LARGE	-0.01	-0.04***	-0.01**	0.02*	0.01	-0.03*	0.02*
	MEDIUM	-0.02***	-0.11***	-0.05***	0.02	0.10***	-0.11***	0.02
	SMALL	-0.02***	-0.13***	-0.06***	-0.02	-0.04	-0.10***	-0.04**
	NOTRADE	0.01*		0.02***				
SLOW	LARGE	-0.02***	-0.05***	-0.02***	0.01	0.00	-0.09***	-0.01
	MEDIUM	-0.00	-0.03***	-0.00	-0.01	0.01	-0.02**	0.01*
	SMALL	0.00		0.02***	-0.02*		-0.03***	
	NOTRADE	-0.01**						
	Constant	-0.01***		-0.03***	-0.00			-0.02***
	# obs	66,885		66,885	85,995			85,995
	Adj R^2	0.033		0.015	0.003			0.001
	Clustered St.Err.	By Stock		By Stock	By Stock			By Stock

Table IA 2.2: Contribution to weighted price discovery: different reference prices

This table presents the summary statistics for the weighted price discovery contribution (WPC) during the pre-opening period for 97 stocks from the TOPIX100 during the sample period of April-May 2013 for different reference prices: opening price and price at 09:30. WPC is attributable to aggressive orders. Aggressive orders in the pre-opening period are defined as follows: (1) all market orders; (2) limit buy orders with a limit price greater than or equal to the prevailing best bid; (3) limit sell orders with a limit price less than or equal to the prevailing ask; (4) any orders submitted when best bid equals best ask (zero imbalance). Aggressive orders during continuous trading session are defined as orders that initiate the transaction (timestamp of the transaction should be equal to the timestamp of the new order entry or timestamp of the price revision): (1) new market orders; (2) limit-to-market orders; (3) new or revised buy (sell) limit orders with a limit price greater (smaller) than the best ask (bid) price ("Cross"); (4) new buy (sell) limit orders with a limit price equal to the best ask (bid) price ("Lock"). We divide all traders into 12 groups on a stock-day basis, as described in Table 2, using information about speed and inventory from the same day's continuous session. We also split traders into 2 categories: traders that participate during the pre-opening period, but do not trade at the opening call auction (Active-w/o-trade), and traders that participate during the pre-opening period and trade at the call auction (Active-w-trade). Order flow data, with order IDs as well as virtual server IDs, are provided by the Tokyo Stock Exchange.

Speed	Inventory	Reference price: opening price			Reference price: price at 09:30		
		Active-w/o-Trade	Active-w-Trade	Total	Active-w/o-Trade	Active-w-Trade	Total
FAST	LARGE	-3.01%	-4.54%	-7.55%	-3.85%	-4.54%	-8.39%
	MEDIUM	-3.55%	-23.11%	-26.66%	-4.18%	-25.24%	-29.42%
	SMALL (HFTs)	-2.56%	-13.67%	-16.23%	-3.10%	-11.00%	-14.10%
	NOTRADE	-0.50%		-0.50%	-0.52%		-0.52%
MODERATE	LARGE	-1.68%	-3.99%	-5.67%	-1.86%	-2.45%	-4.31%
	MEDIUM	-2.95%	-9.90%	-12.85%	-3.21%	-7.24%	-10.45%
	SMALL	-2.40%	-11.21%	-13.61%	-2.47%	-11.66%	-14.13%
	NOTRADE	-0.42%		-0.42%	-0.35%		-0.35%
SLOW	LARGE	-2.55%	-5.12%	-7.67%	-2.75%	-5.70%	-8.45%
	MEDIUM	-1.32%	-3.31%	-4.63%	-1.46%	-3.60%	-5.06%
	SMALL	-0.89%	-1.12%	-2.01%	-1.46%	-0.90%	-2.36%
	NOTRADE	-2.20%		-2.20%	-2.47%		-2.47%