IEX's Speed Bump and Its Effect on Adverse Selection

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Abstract

IEX's speed bump includes two layers of delays: a fixed delay on displayed orders, and a contingent delay on some non-displayed order types, which is triggered when the Crumbling Quote Signal forecasts an unfavorable price change. We build a simple statistical model to show why both delays are essential in reducing adverse selection, and empirically assess their joint effect using the publicly available trade and quote (TAQ) data from January to March 2017. We find that compared with other nine major U.S. exchanges, IEX is among the venues with the lowest adverse selection for small- and medium-sized stocks. For large-caps, IEX's performance depends on the physical time interval used for evaluation, where it outperforms most exchanges within 5 seconds after a trade occurs.

Keywords: Investors Exchange (IEX), speed bump, latency delay, adverse selection, price impact
JEL Classification: D47, G14

> The 350-microsecond delay…ensured that IEX would be faster to see and react to the wider market than even the fastest high-frequency trader, thus preventing investors' orders from being abused by changes in that market.
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> —Michael Lewis, Chapter 6: How to take billions from Wall Street, *Flash Boys: A Wall Street Revolt*, W. W. Norton & Company, 2014, p. 177

1. Introduction

A speed bump, formally known as a latency delay, slows down the processing of orders after they arrive at a trading venue (Harris, 2013). In other words, it artificially increases the exchange latency.[1] While exchanges like the NYSE exerted efforts to be faster, the Investors Exchange (IEX)—lionized in Michael Lewis' *Flash Boys*—has worked against this trend. This has helped IEX grow its market share, first as an alternative trading system (ATS) from October 25, 2013, then a lit market as of June 17, 2016.

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[1] In general, latency means the time passed between an event and an action upon that event (Harris, 2015, p. 54). For example, Hasbrouck and Saar (2013) view latency as the time it takes to "learn about an event, generate a response, and have the exchange act on the response". Specifically, Foucault, Pagano, and Röell (2013, p. 38) define latency as the time passed between a quote update and the quote announcement.

The purpose of IEX's speed bump is to protect liquidity suppliers from two types of *latency arbitrage* by some high-frequency traders (HFTs).[2] The first type relates to exploiting stale quotes. Suppose some HFTs with direct news feeds know or predict with precision the new national best bid and offer (NBBO) before other traders, who rely on slower feeds such as the Securities Information Processors (SIPs). If a venue with old NBBO has yet to update its quotes, HFTs can race to it, trade against its standing orders, and close their position at another venue that offers the new NBBO. The second type of arbitrage relates to soon-to-be-stale quotes, commonly known as multi-venue front-running. Suppose a large order is sliced into smaller child orders, which are then routed to venues geographically apart. HFTs can use pattern-recognition algorithms to detect one slice, take the liquidity from other markets, move the best quotes, eventually trade against the slowly coming child orders at an unfavorable new price. In both cases, the uninformed liquidity supplier is adversely selected or gets run over; that is, they turn out to buy right before a price decline or sell right before a price rise, thus lose out to the informed (Parlour and Rajan, 2010).

These arbitrages result from a difference in *to-exchange latency*: some traders are faster than others *en route* to a trading venue. And they enjoy the speed advantage through superior hardware, algorithms, faster routes like microwave or laser network, proximity hosting, or even colocation (O'Hara, 2015). To counteract the benefits from reducing to-exchange latency, a speed bump increases the exchange latency, therefore render the total latency unchanged.

This seemingly straightforward mechanism, however, has sparked much controversies since its launch. One attack is that it causes quote fading or phantom liquidity, which says while orders await execution during the delay, liquidity providers can revise their quotes. But this is not an IEX-initiated problem. First, quote cancels at fast speed is one defining feature of the automated trading era. For example, Potters and Bouchaud (2003) find that in June and July 2002, the number of cancel rate was nearly 5 times the execution rate for QQQ, one of the most active ETFs. Second, quote fading can protect liquidity providers. For instance, Hendershott and Jones (2005) document that the Intermarket Trading System (ITS) Plan mandated that when a better price is offered elsewhere, orders must be routed there, which is similar to the order protection rule of the Reg NMS in 2005. At the same time, the market makers in the receiving market were granted up to 30 seconds to respond, after which it can simply cancel the order, and protects itself from trading against an unfavorable price.[3] Similarly, in IEX's own study, Aisen (2017, p. 9) deems that the ability to cancel orders helps fast market makers to avoid predatory trading in a proactive way.

To validate IEX's merits, scholars have come up with several models based on the delay IEX implemented. Brolley and Cimon (2018) considers the decision-making of informed and non-informed traders to route a limit and/or market order to either a delayed or a non-delayed exchange. Aldridge and Krawciw (2017) study how a delayed exchange with special types of dark orders prevents high-frequency sniper from adversely select liquidity traders. At last, Manrique et al. (2017) cast the operation of IEX into a Minority Game that has perpetual order imbalance.

[2] Or, using the terminology in Aisen (2017), the stale quote arbitrage and crumbling quote arbitrage, respectively; the first one is also called the direct feed arbitrage in Bartlett and McCrary (2017). These types of arbitrage existed long before the emergence of HFT. For example, NASDAQ's Small Order Execution System designed for small investors was a place for stale quote arbitrage, because some broker/dealers (called SOES bandits) can see the quote changes earlier than others who don't have access to this electronic system; see Schwartz (2001). More elaboration in the case of IEX is given in Section 3.

[3] For more details, see SEC, "Memorandum of Rule 611 of Regulation NMS," pp. 7-8; available at *https://www.sec.gov/spotlight/emsac/memo-rule-611-regulation-nms.pdf*.

The first two allows the market maker to change quotes when new information arrives, and both predict a decrease adverse selection; the lasts one indicates the price may change asynchronously and in different patterns across exchanges.

Nevertheless, all models may have left out some features in IEX, and their predictions must be interpreted with care. As a result, we provide a detailed review of IEX's business model, which we find is a trilogy of a fixed delay on displayed orders; heavy use of dark, pegged orders; and a contingent delay on some of these non-displayed order. We then describe IEX's business model as to minimize the time window a resting order may be adversely selected. We proceed to empirically test the predictions from the theory models, and find that IEX have smaller adverse selection costs than most exchanges for small- and medium-sized stocks, but not necessarily for large caps. We also analyze the whether IEX's trades take place when the order flow toxicity is low.

The paper is organized as follows. Section 2 gives more details about IEX's speed bump and compares it with similar schemes in the United States and Canada. Section 3 briefly reviews three theoretical models, and sets up an alternative model from the perspective of IEX itself. Section 4 presents the data and summary statistics, and and proposes equations based on these models that can be readily tested. Section 5 provides the empirical findings, and the last section ends with some concluding remarks.

2. The Business Model of IEX

Retail stock investors, being capital constrained, face the dual dearth of speed and computing power (e.g. to calculate their own NBBO). And their potential need to counteract these disadvantages creates a business opportunity: exchanges can charge a small amount for the service that protects these investors from predatory trading.

Interestingly, the equity market comes only after the foreign exchange (FX) market to install an explicit speed bump. In April 2013, a new FX platform called ParFX initiates a mechanism named "Green Room" whereby incoming orders are slowed down randomly by 20–80 milliseconds before they are consigned to the matching engine (Mannix, 2016).[4] Later in August, a competing platform called EBS rolled out a similar mechanism called "latency floor," and it batches orders every 1, 2 or 3 milliseconds before they are matched.[5]

While earlier speed bumps in the FX market consist only of a delay, the one adopted by IEX embraces richer features under the principle of minimizing the information advantage of incoming orders and the information leakage of resting orders. Before we proceed to extant theoretical models and our empirical analysis, it is necessary to scrutinize IEX's actual business model—a trilogy of the delay itself, dark orders, and the crumbling quote signal. In addition, the latter two elements have experienced a few modifications and will continue to evolve.

[4]See also Wanfeng Zhou, and Nick Olivari, "Exclusive: EBS take new step to rein in high-frequency traders", *Reuters Business News*, August 23, 2013; available at *http://www.reuters.com/article/us-markets-forex-hft/exclusive-ebs-take-new-step-to-rein-in-high-frequency-traders-idUSBRE97M0YJ20130823*.

[5]EBS, *EBS Dealing Rules, Appendix: EBS Market*, October 2015; available at *http://www.ebs.com/~/media/Files/I/Icap-Ebs/rulebooks/201603-05-EBS%20Dealing%20Rules%20EBS%20Market%20Appendix%20291015.pdf*.

2.1. *The Delay*

The length of delay adopted by IEX, is fixed at 350 microseconds.[6] According to Bishop (2017), technically, IEX needs 300 microseconds to learn a quote change and mark its pegged orders to the new price. And an additional 50 microsecond is added to allow enough time to response. Moreover, according to Ding, Hanna, and Hendershott (2014), 300 microseconds is also the time needed to execute a market order.

This delay translates to the 38-mile optical fiber IEX coiled between its point of present (POP) in Secaucus and its trading platform in Weehawken. Referring to the story that adding an exchange latency strategically counteracts HFTs' cutting of their to-exchange latency, this choice is easy to understand. Note that the three major US exchange groups—NYSE, NASDAQ, Cboe (Bats and Direct Edge)—all have their data centers located in New Jersey. Specifically, the NYSE Euronext Data Center sits in Mahwah; the NASDAQ Data Center is in Carteret; the Equinix NY5 Data Center, which holds Bats (after its 2015 migration), Direct Edge and the IEX POP, is in Secaus; the IEX trading platform is at CenturyLink NJ2X Data Center in Weehawken; see Figure 1 for an illustration. The theoretical, straight-line distance between any pair of locales is less than 38 miles: 35 miles from NYSE to NASDAQ; 21 miles from NYSE to Direct Edge or IEX POP, and a further 16 miles to NASDAQ; 3 miles from IEX POP to IEX trading platform.

In lobbying to become a lit market, IEX attracted critics from the legal sphere. First, a delay is in conflict with what Reg NMS Rule 600 requires: immediacy. As a result, the US Stock Exchange Commission (SEC) has to reinterpret the term and announced that a "*de minimis* intentional delay" is admissible.[7]

Second, installing a fixed, rather than a random delay as suggested by Angel, Harris, and Spatt (2015) and Budish, Cramton, and Shim (2015), is to maintain IEX's status as an *automated* trading center so that the Reg NMS Rule 611, or the "trade-through rule," still applies (Mannix, 2016).[8] By this rule, when a lit order arrives at IEX but the exchange cannot offer a price better than the NBBO, IEX must route the order to the venue(s) with NBBO, and this routing is also subject to a 350-microsecond delay. In contrast, two Canadian markets that adopt a random delay are labelled as failed to "provide automated trading functionality," thus are no longer qualified for the Canadian version of Rule 611, the Order Protection Rule (OPR).[9]

One concern about a random delay is that the randomness may put the exchanges into the same principal-agent problem NYSE specialists were in. As Stoll (2006) has pointed out, in the absence of automation, the specialists own some leeway in deciding whether and when to execute their customers' orders, thus have an incentive to trader for their own benefits. By the same token, an exchange may exploit the discretion brought by the random delay.

Nevertheless, when we factor in the internal engine latency of HFTs and trading centers, as well as the uncertainty in transmitting data packets under time-varying traffic conditions, even a nominal fixed delay becomes virtually stochastic. For example, one exchange may have limited processing capacity, such that HFTs may randomly lose their first-mover advantage to their peers.

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[6] 350 microseconds is equal to 0.35 millisecond, or $3.5 \quad 10^{-4}$ second.

[7] See SEC, "Commission Interpretation Regarding Automated Quotations Under Regulation NMS," *Code of Federal Regulations (CFR)*, Title 17, Part 241, March 2016; available at *https://www.sec.gov/rules/interp/2016/34-78102.pdf*.

[8] Angel, Harris, and Spatt (2015) propose a delay of "0 to 10 milliseconds" (p. 26). See also Reg NMS, CFR Title 17, Chapter II, Part 242, Section 242.600; available at *https://www.law.cornell.edu/cfr/text/17/242.600*.

[9] IIROC, *List of Protected and Protected Marketplaces*, June 23, 2016; available at *http://www.iiroc.ca/Documents/2016/298bb01f-d0e9-4cba-a649-18c92c9522df_en.pdf*.

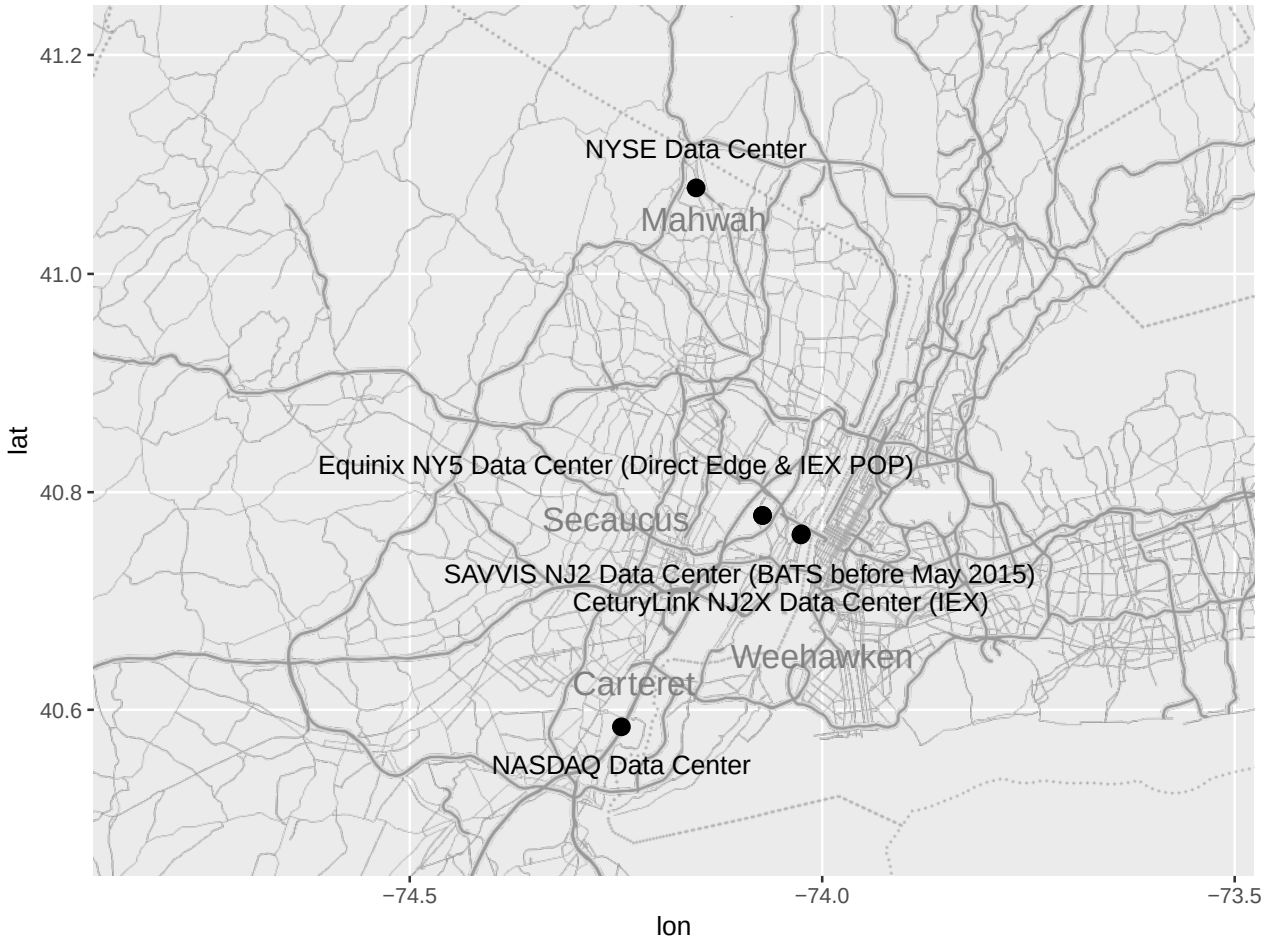

Figure 1: Locations of Major Data Centers

Source: Adapted and updated from Durbin (2010, p. 125, 135) and Bartlett and McCrary (2017); redrawn in R using the Stamen type of map.
Notes: NYSE's Euronext Data Center is located at 1700 MacArthur Boulevard, Mahwah, Bergen County, New Jersey; the NASDAQ Data Center is located at 1400 Federal Boulevard, Carteret, Middlesex County, New Jersey; the data centers of IEX, Direct Edge, and Bats (after migration) sits at Equinix NY5 Data Center, at 800 Secaucus Road, Secaucus, Hudson County, New Jersey; the old data center of Bats is at SAVVIS NJ2 Data Center, located at 300 Boulevard East, Weehawken, Hudson County, New Jersey; IEX's trading platform sits in the nearby Equinix NY5 Data Center, at 800 Secaucus Road, Secaucus, Hudson County, New Jersey.

A side piece of evidence can be found in Ding, Hanna, and Hendershott (2014), where the quote updates recorded in the NASDAQ SIP and a direct feed server co-located with Bats have different time stamps; although the distance between the two exchanges is fixed, the time difference between the two records of the same trade follows a right-skewed distribution, instead of being a fixed number.

2.2. *Crumbling Quote Signal*

Looking from the map shown in Figure 1, we can see that the 350 microsecond delay can forestall the fastest arbitrageurs to IEX. But speculative trading in general are not that fast; instead, the quotes of a stock in different exchanges move towards a new NBBO piecemeal (Bishop, 2017). In fact, IEX found that in 2014, the percentage of Midpoint Peg orders that were adversely selected jumped from 3% in January to 11% in July.[10]

As a response, IEX developed a "Crumbling Quote Signal" (also known as the IEX Signal). The idea is to count how many lit markets are at NBB or NBO, see whether these counts changes occur within a time frame, and use these variables along with other indicators to predict whether the NBBO from IEX's perspective is about to change. From November 2014 to the writing of this paper, the signal has experienced four revisions, which are summarized in Table 1.

The most recent version uses a logistic model to forecast if IEX's quotes will change, where the explanatory variables include 4 time-stamped predictors and 4 event variables related to the eight exchanges—NYSE, NYSE Arca, NASDAQ, NASDAQ BX, BZX, BYX, EDGA, and EGDX. Although for the sake of simplicity, we still adopt the notation NBB and NBO here, it should be emphasized that IEX as well as other venues, tend to build their own consolidated tape based on quote information from direct feeds. Take the prediction of downward tick for example, the time-stamped variables include (1) $\#NBB_t$ and (2) $\#NBO_t$, which are the counts of exchanges that have the best bid and ask; (3) $\#NBB_t \quad \#NBB^{\max}_{[t-1,t]}$ and (4) $\#NBO_t \quad \#NBO^{\min}_{(t-1,t]}$, where $\#NBB^{\max}_{(t-1,t]}$ is the maximum number of exchanges reside at NBB during the 1 millisecond window before the current time stamp, and $\#NBO^{\min}_{[t-1,t]}$ is the minimum number of exchanges reside at NBO during the 1 millisecond prediction window. The four binary event variables, which evolves from the contingency table approach tested in the model development stage, include (1) EP_{n-1} and (2) EN_{n-1}, which equal 1 if the last event in the prediction window was a venue leaves and joins the NBB; and (3) EP_{n-2} and (4) EN_{n-2}, which equal 1 if the next to last event is a venue leaves and joins the NBB. Variables used to predict an upward tick can be found analogously.

To assess whether the signal functions well, Wah et al. (2017) compare IEX's quote stability with other lit markets in US. They pick up a 2-millisecond window before an NBBO change as a period with unstable quotes. Using the TAQ data from January to March 2017, it is found that the percentage of trades executed outside unstable quotes versus inside are the highest in IEX.

The predictability of prices changes (at least to some degree), however, is in direct conflict with a standard modelling assumption that the price follows a martingale; in other words, the price change is purely random.

[10] Daniel Aisen, "The Genesis of an Order Type," *Quant Finance*, April 22, 2015; available at *https://blog.quantopian.com/the-genesis-of-an-order-type-by-daniel-aisen/*.

Table 1: Evolution of the Crumbling Quote Signal

No.	Effective Period	Model for Predicting A Downward Tick	Restrictions	Prediction Window	Firing Window
1	Nov 2014–Sep 2015	$\#NBB_{t-5}$ $\#NBB_t$ 3	$Ask_t > Bid_t, NBB_t > 1$ NBO_t $NBB_t = 0.01$ $NBB_t = NBB_{t-5}, NBO_t = NBO_{t-5}$	5ms	10ms
2	Sep 2015–Aug 2016	Logistic: $F(\mathbf{x}; \hat{\boldsymbol{\beta}})$ $\bar{p}$ $\mathbf{x}$: $\#NBB_t, \#NBB_{t-1}, \#NBO_t, \#NBO_{t-1}$	$Ask_t > Bid_t, Ask_t$ Bid_t $\bar{S}_{30day}$ $\bar{p}, \hat{\boldsymbol{\beta}}$ estimated from historical data	1ms	10ms
3	Aug 2016–Mar 2017	Logistic: $F(\mathbf{x}, \mathbf{z}; \hat{\boldsymbol{\beta}})$ $\bar{p}$ $\mathbf{x}$: $\#NBB_t, \#NBB_{t-1}, \#NBO_t, \#NBO_{t-1}$, $D3_{t-1}$; $\mathbf{z}$: EN_{n-1} EN_{n-2}*	$Ask_t > Bid_t$ $\bar{p}, \hat{\boldsymbol{\beta}}$ estimated from historical data	1ms	2ms or a price change
4	Mar 2017–present	Logistic: $F(\mathbf{x}, \mathbf{z}; \hat{\boldsymbol{\beta}})$ $\bar{p}(Ask_t$ $Bid_t)$ $\mathbf{x}$: $\#NBB_t, \#NBO_t, \#NBB_t$ $\#NBB^{\max}_{(t-1,t]}$, $\#NBO_t$ $\#NBO^{\min}_{(t-1,t]}$ $\mathbf{z}$: $EP_{n-1}, EN_{n-1}, EP_{n-2}, EN_{n-2}$*	$Ask_t > Bid_t$ $\bar{p}, \hat{\boldsymbol{\beta}}$ estimated from historical data Consider only 8 exchanges.**	1ms	2ms or a price change

Source: Wah et al. (2017) and Bishop (2017).

Notes: The table only presents the models employed to predict a downward tick; models that serve to forecast an upward tick can be set up analogously. The logistic function takes the form $F(\mathbf{x}; \boldsymbol{\beta}) = 1/\left[1 + \exp(\ \mathbf{x}'\boldsymbol{\beta})\right]$; to do real-time prediction, first obtain an estimate of $\boldsymbol{\beta}$ by maximum likelihood approach, inserting historical observations of $\mathbf{x}$. The last adjustment of the crumbling quote signal algorithm was done during March 24–28, 2017, see *https://iextrading.com/trading/alerts/2017/006/* for details.

NBB_t and NBO_t are the national best bid (NBB) and national best offer (NBO) prices observed by IEX; $\#NBB_t$ and $\#NBO_t$ are the numbers of exchanges that show NBB and NBO at time t; similarly, $NBB_{t-\tau}$ and $NBO_{t-\tau}$ are the numbers of exchanges that show NBB and NBO at time t τ, τ is measured in millisecond (ms).

The prediction window is the time interval used to compute the the model; and if the criteria (inequality) in column 3 holds, then IEX turns on the signal to restrict the trading of some pegged order. The firing window is the length that the signal is on. The logistic model, namely, estimate $\hat{\boldsymbol{\beta}}$ a logistic regression using historical data, and the probability cut-off is chosen to equate true positives (there is a price change and the model predicts it) and false positives (there is no price change but the model predicts one). $\bar{S}_{30d}$ are average spread for a stock in the past 30 days.

*$D3_{t-1}$ is the number of exchanges among Bats, EDGX, NASDAQ that resides in NBB, thus takes either 0, 1, 2, or 3. EN_{n-1} and EP_{n-1} (EN_{n-2} and EP_{n-2}) are binary variables; they denote the last (penultimate) event in the prediction window is a venue leaves (N for negate) and joins (P for plus) the NBB, respectively. Similarly, EN_{n-1} EN_{n-2} is a binary variable; it equals one when the last *two* events in the prediction window are both that a venue leaves the NBB.

**The 8 exchanges are: NYSE, NYSE Arca, NASDAQ, NASDAQ BX (inverted), BYX (inverted), BZX, EDGA (inverted to flat fee from June 1, 2017), EDGX. The details of these exchanges and their fee schedules are summarized in Table 2.

2.3. *Dark Orders*

Again, as Angel, Harris, and Spatt (2015) has argued, the huge capital outlay on "speedy technologies" has created barrier to entry in the sub-second trading industry. This, while puts capital-constrained small traders in an disadvantaged position, also creates a business opportunity for the exchange: it can offer additional service to small traders to help them circumvent latency arbitrageurs. Since the demand of such traders is potentially large, the cost of the offer can be diluted to a low figure. The most simple way to implement, is to integrate the service to special order types.

The use of dark orders in IEX, is a heritage from the period when it was an alternative trading system (ATS). Non-discriminatory disclosure of information, according to Angel, Harris, and Spatt (2011), reinforces the informational advantage of high-frequency traders; and dark orders, through reducing the information disclosure from retail traders, give protection to the uninformed order flow these dark venues aim to attract.

In the case of IEX, while market orders are non-displayable as usual, limit orders can be displayed, partially displayed, or completely dark. Besides, IEX provides three types of pegged orders that are completely non-displayed—Midpoint Peg Orders (M-Peg), Primary Peg Orders, and Discretionary Peg Orders (D-Peg)—with which traders can also specify a limit price for each.[11] Figure 2 illustrates the proportion of different types of orders in December 2016, where the total share of dark volume amounted to an astonishing 80%. The implications of such heavy use of dark and pegged orders are: first, IEX's displayed limit order book and the quoted spread may be less informative than other lit venues; second, it may have limited role in price discovery since the pricing of pegged orders is derived from other markets.

Specifically, the Primary Peg order type has experienced a staggered revision during March 27 to April 3, 2017.[12] Before the change, a Primary Peg is pegged at the NBB (for buy orders) or NBO (for sell orders). After the change, a Primary Peg is pegged to one unit away from the NBB (for buy orders) or the NBO (for sell order); it can trade at this price no matter what, or the NBBO when the quote is stable. Otherwise, when the quote is about to change, it resides at either one price unit below the NBB (for buy orders) or one price unit above the NBO (for sell order). M-Peg stays at the midpoint of the NBBO, until an incoming order trades against it. The D-Peg is a combination of the two: when it arrives, it checks the liquidity at the midpoint; if it is not executed or only partially filled, the unfilled part goes to reside at NBB or NBO, and queued after other orders when the quote is stable, and at one unit away from NBB or NBO when the quote is about to crumble. The D-peg was created to combat increasing adverse selection in the M-Pegs.[13]

IEX relies heavily on these dark orders compared with the rest of lit markets in US: in the last quarter of 2016, over 60% of its trades and 70% of its volume are non-displayed, while other exchanges have a share of 20% or less (Wah et al., 2017). The presence of tremendous dark liquidity renders the quoted spread on IEX a less relevant measure of transaction cost to the liquidity demander. Moreover, IEX's rich liquidity at the midpoint corresponds to both a short duration and a

[11] IEX, *Investors Exchange Rule Book*, Rule 11.190: Orders and Modifiers, September 20, 2017; available at *https://iextrading.com/docs/Investors%20Exchange%20Rule%20Book.pdf*.

[12] IEX, "Update to IEX Primary Peg Order Type and Locked/Crossed Behavior for Primary and Discretionary Pegs", *IEX Trading Alert #2017 - 007*, March 20, 2017; available at *https://iextrading.com/trading/alerts/2017/007/*.

[13] Daniel Aisen, "The Genesis of an Order Type," *Quant Finance*, April 22, 2015; available at *https://blog.quantopian.com/the-genesis-of-an-order-type-by-daniel-aisen/*.

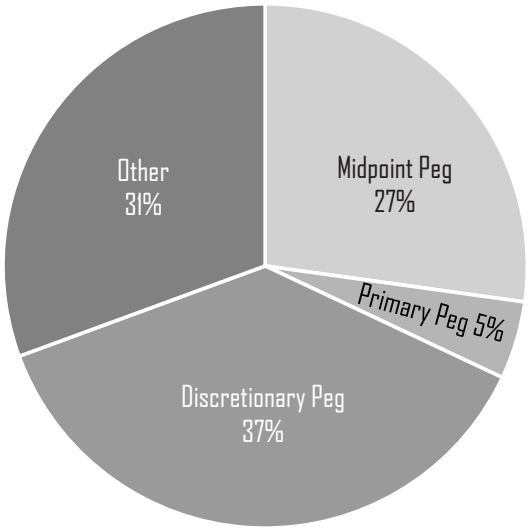

Figure 2: Proportions of Major Order Types on IEX (December 2016)

Source: Adapted from Table 1 of Aldrich and Friedman (2017).
Notes: The proportion of an order type is calculated by its share of executed volume on IEX. The *Other* category includes limit and market orders, 60% of which are non-displayed. In total, around 80% of the orders are non-displayed.

small volume at NBB or NBO.

At the time of this writing, IEX plans to launch a displayed but not routable order called "Market Maker Peg Order," or MM Peg. As the name suggests, IEX-registered market makers are eligible to use this type of order, whose price is adjusted if it lies outside a price band.[14]

2.4. The Fee Structure

Equity exchanges in the United States tend to consolidate with each other to form larger exchange groups, each of which offers differentiated trading models and fee structures to cater to different needs.[15] This results in an oligopoly in the stock trading sector that neither a Betrand nor Cournot duopoly model—featuring a price and a quantity competition, respectively—could perfectly capture.[16] Table 2 provides a summary of the characteristics of the 13 exchanges. Among them, NYSE Arca ranks 1st in exchange-traded funds (ETFs) trading, where 1/3 of non-FINRA/TRF dollar volume takes place there; NASDAQ PSX has a unique Price Setter Pro Rata algorithms. In

[14]See IEX, "Introducing IEX Market Maker Peg Order Type," IEX Trading Alert #2017–025, July 24, 2017; available at *https://iextrading.com/trading/alerts/2017/025/*. IEX, "Proposed rule change to introduce a new Market Maker Peg Order"; available at *https://iextrading.com/docs/rule-filings/SR-IEX-2017-22.pdf*.

[15]National Stock Exchange (NSX) was acquired by NYSE February 1, 2017; therefore, we exclude it from our empirical analysis. Bats and National Stock Exchange are both owned by CBOE Holdings, Inc., where CBOE's acquisition of Bats was completed on February 28, 2017; however, the CBOE Stock Exchange itself stopped trading since April 30, 2014. The Chicago Stock Exchange is owned by CHX Holdings, Inc.; NASDAQ, NASDAQ BX, and NASDAQ PSX are owned by Nasdaq, Inc.; NYSE, NYSE Arca, NYSE American, and NYSE National are owned by Intercontinental Exchange Inc. Among these 13 exchanges, NYSE only trades Tape A shares; before converted to a delayed exchange, NYSE MKT (now NYSE American) only trades in Tape B shares.

[16]Even in early 2000s, Madhavan (2002) commented that "intermarket comparisons are difficult"; for example, behaviors like order-flow preferencing may render predictions from simple theoretical models invalid.

terms of fee structure, only NASDAQ BX and Cboe BYX maintain the maker-taker fee schedule; Cboe EDGA, an inverted venue until the end of May 2017, begins to charge a flat fee afterwards.

By the end of 2017, IEX charged zero fees on lit limit and market orders, but a low fee of 0.09 cents per share for all the dark order types; NYSE American uses the same pricing strategy and even charges less. This can also stop HFTs from taking advantage of liquidity suppliers: if they submit market orders, they are subject to a delay; if they submit a pegged order that is exempt them from the delay, they must pay a fee. However, as the crumbling quote signal is a statistical model (this will elaborated in the next section), it still leaves some space for predatory transactions when the quote is about to change (Aisen, 2017). As a response, IEX launched a Crumbling Quote Remove Fee on January 1, 2018. This mechanism charges traders 0.3 cent per share for their removal of lit liquidity when the Signal is firing, but only if their trading volumes exceed a certain limit.[17]

2.5. A Comparison with Other Speed Bumps

Recently, other variations of speed bumps arise: delays can be imposed on some order types, and/or some cohorts of traders; and the length of delay can be randomized, rather than fixed. In Canada, two equity exchanges have implemented their versions of speed bumps. One is the Aequitas NEO Exchange established in March 2015, and its NEO-N market (also known as Aequitas NEO Book) levies a 3 to 9 milliseconds random delay on some HFTs. This market is inverted: for stocks worth more than $1, it grants a 0.15 cent per share rebate to liquidity taker, and charges a 0.18 cent per share fee on liquidity maker.[18]

Another exchange adopted a similar delay in Canada is TSX Alpha, which launched its 1 to 3 milliseconds random delay in September 2015.[19] However, Post-Only orders—limit orders that are not marketable upon entry—are exempted from the delay.

Using data around TSX Alpha's launch, Chen, Foley, Goldstein, and Ruf (2017) argue against the speed bump. However, gauging the pure effect of the delay is difficult, because at the same time Alpha turned to an inverted venue, i.e., one with a taker-maker pricing. The issue is complicated further by the exchange's two-phase introduction of this inverted fee schedule.[20] Moreover, the employment of a random delay rendered the venue no longer eligible to the Order Protection Rule, which implies that the orders there may not executed at the best prices. Furthermore, although Post-Only Orders are exempted from the speed bump, these orders must specify a minimum number of stocks, depending on the price of the stock, ranging from 200 for stocks priced over $125 and 20,000 for those less than $0.10.[21] This may increase brokers' inventory costs, therefore reduces the attractiveness of the speed bump.

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[17] See IEX, "IEX Fee Schedule Updates Operative January 1, 2018 (Crumbling Quote Remove Fee)," IEX Trading Alert #2017-056, December 19, 2017; available at *https://iextrading.com/trading/alerts/2017/056/*. A trader is subject to the fee if both of the following conditions are met: (1) in a single month, when the Signal is on, more than 1,000,000 shares are removed from IEX; (2) the volume in (1) amounts more than 5% of its total monthly trading volume on IEX.

[18] Aequitas NEO Exchange Inc., *Membership and Trading Fee Schedule*, Section 3.2, July 1, 2017, avaiable at *https://www.aequitasneo.com/documents/en/trading-data/NEO-Membp-and-Trading-Fee-Sched-July-1-2017.pdf*.

[19] The delay is either of 1, 2, or 3 millisecond(s), rather than a number continuously distributed over the 1 to 3 milliseconds interval.

[20] See TMX, "TSX Alpha Exchange Announces New Fee Schedule," *Equities Trading Notice*, September 8, 2015. Available at *https://www.tsx.com/resource/en/1197*.

[21] See TSX, *TSX Alpha Exchange—Minimum Posting Sizes*, August 19, 2015; available at *https://www.tsx.com/resource/en/1185*; see also *https://www.tmxmoney.com/en/research/post_only.html*.

Table 2: Fees/Rebates for Tape A Symbols of the Thirteen Lit Equity Markets

No.	Exchange	Formerly Known as	Abbreviated as	MIC Code	Symbol in TAQ	Maker-Taker Fees (cents/share) +: take fee : take rebate	Maker-Taker Fees (cents/share) : make rebate +: make fees
1	NYSE		NYSE	XNYS	N	+0.23	-0.15 to -0.21
2	NYSE Arca	Archipelago Exchange, Arca	ARCA	ARCX	P	+0.30	-0.21 to -0.30
3	NYSE American	Amex, NYSE MKT	MKT	XASE	A	+0.00(l); +0.02(d)	+0.02
4	NYSE National*	National Stock Exchange	NSX	XCIS	C	+0.30	-0.00
5	NASDAQ		NSDQ	XNGS	T/Q	+0.20	-0.14 to -0.25
6	NASDAQ BX	Boston Stock Exchange	BX	XBOS	B	-0.14	+0.18 to +0.15
7	NASDAQ PSX	Philadelphia Stock Exchange	PSX	XPHL	X	+0.26 to +0.30	-0.23 to -0.30
8	Cboe BYX	Bats BYX	BYX	BATY	Y	-0.29	+0.25 to +0.29
						-0.08	+0.18
9	Cboe BZX	Bats BZX	BZX	BATS	Z	+0.30	-0.20 to -0.25
10	Cboe EDGA**	Direct Edge A, Bats EDGA	EDGA	EDGA	J	-0.04	+0.06 to +0.05
						+0.05	+0.00 to +0.05
11	Cboe EDGX	Direct Edge X, Bats EDGX	EDGX	EDGX	K	+0.30	-0.23 to -0.32
12	Chicago Stock Exchange		CHI	XCHI	M	+0.30	-0.20
13	Investors Exchange		IEX	IEXG	V	+0.00(l); +0.09(d)	+0.00(l); +0.09(d)

Source: The list of US exchanges are taken from SEC, *Fast Answers: National Securities Exchanges*, April 2017; available at *https://www.sec.gov/fast-answers/divisionsmarketregmrexchangesshtml.html*. NYSE fee schedule is available at *https://www.nyse.com/markets/nyse/trading-info/fees*. NASDAQ fee schedule is available at *https://www.nasdaqtrader.com/Trader.aspx?id=PriceListTrading2*. Chicago Stock Exchange fee schedule is available at *http://www.chx.com/LiteratureRetrieve.aspx?ID=119763*.

Notes: Inverted venues, which adopt a taker-maker fee schedule, are marked in shade. MIC Code, or Market Identifiers Codes, can be accessed via *http://www.iotafinance.com/en/ISO-10383-Market-Identification-Codes-MIC.html*. The first line of maker-taker fee schedule is the value before our sample period; and the second line shows the value as of December 2017.

* The National Stock Exchange stopped trading from February 1, 2017 as it was acquired by NYSE and is later renamed as NYSE National. The fee schedule before the acquisition, as shown in the table, is available at *https://www.nyse.com/publicdocs/nyse/regulation/nyse/NYSE_National_Schedule_of_Fees.pdf*.

**EDGA Exchange turned from an inverted venue to a flat-fee exchange since June 1, 2017; see Bats, *New Release: Bats Announces Fee Overhaul of EDGA Equities Exchange*, available at *http://cdn.batstrading.com/resources/press_releases/Bats-EDGA-Reprice-FINAL.pdf*. The differences between the four exchanges (BZX, BYX, EDGX, EDGA) owned by Bats can be found at *https://markets.cboe.com/us/equities/membership/pricing/*.

In the US, NYSE MKT copied IEX's model and its application for the same 350-microsecond delay was finally approved by the Securities and Exchange Commission (SEC) on May 16, 2017; and following this approval, the exchange is renamed as NYSE American. At the same time, it adopts a more attractive maker-taker fee structure than IEX, charging both 0.02 cents for taking and removing dark liquidity.[22] At the time of this writing, the Chicago Stock Exchange is also pressing hard to install the 350-microsecond delay, which aims to slow down liquidity takers.[23]

The attempt to segment informed and uninformed traders, as we can see, can be accompanied not only through the delay itself, but also by special order types and by ditinguishing different types of traders. For example, IEX's delay applies to inbound displayed orders; hidden-pegged orders, which liquidity traders are more likely to employ, are exempted from this delay. Also, the delay of Aequitas's NEO-N market explicitly applies to liquidity-taking HFTs, who are more likely to be informed. As commented in Comerton-Forde, Malinova, and Park (2017), intends to forestall traders who "want to take liquidity at multiple venues".

Despite these differences, both the US and Canadian markets have been conservative towards speed bump filings, as applications for such delays are implemented only in small exchanges, small in the sense of dollar trading volumes. By the end of 2016, IEX's share hovers around 2.0%; the share of NYSE American (then named NYSE MKT) is less than 0.5%; in Canada, TSX Alpha's market share fluctuates around 6–7%, while the NEO-N accounts for only 1–2%.[24]

3. An Explanatory Model on IEX: Two Layers of Delay

The speed bump has sparked tremendous debate on the ecology of the US equity market, yet its potential effects are not fully understood. Recently, the academia has come up with a few new models to examine the effect of such sub-second delays on spreads, adverse selection, and price discovery. However, none account for the crumbling quote signal. All of the models focus on traders' behavior under the delay; and the equilibrium conditions, if any, are derived from an indifference of payoffs between different order or trader types.

Our model contrast the latency delays faced by unprofessional investors that use the cheap SIP feed the professional ones who use direct feeds from the exchanges.[25]

3.1. Extant Models

Here we only provide a synopsis for each of the three extant models, but leave the details to the appendix. Among the models, Brolley and Cimon (2018) extend the classic model Glosten and Milgrom (1985) to a two-exchange set-up, where the slow exchange delays market orders with some probability. Aldrich and Friedman (2017) model the fact that the bulk of trading in IEX happens at the midpoint, and frames the order imbalance of M-Peg orders as a dealer's problem similar to Garman (1976). In contrast, Manrique et al. (2017) uses a minority game model where past trading information is announced with a delay. Both Brolley and Cimon (2018) and Aldrich and Friedman

[22] NYSE American, *Fact Sheets*, available at *https://www.nyse.com/publicdocs/nyse/markets/nyse-american/NYSE_American_Fact_Sheet.pdf*.

[23] Matt Levine, "Speed Bumps Are the Hot New Thing for Exchanges", *BloombergView*, August 31, 2016; available at *https://www.bloomberg.com/view/articles/2016-08-31/speed-bumps-are-the-hot-new-thing-for-exchanges*.

[24] See ITG, Canadian Microstructure Review (Fourth Quarter 2016), February 2017, available at *http://www.itg.com/assets/ITG_Canada_Microstructure_Q4_2016.pdf*.

[25] Angel (2018) documents that the cost of SIP on real-time data for a typical professional and an unprofessional investors are $92 and $3 per month at the maximum.

Table 3: The Extant Speed Bumps in US and Canada (in Order of Appearance)

No.	Exchange	Country	Effective since	Length of Delay	Round Trip	Exempted Order Types	Additional Protection	Maker-Taker Fees		Other Features
								Take	Make	
1	IEX	US	Oct 25, 2013	Fixed 350 microseconds	2	Midpoint Peg, Primary Peg, Discretionary Peg	Crumbling Quote Signal	+0.00(l); +0.09(d)	+0.00(l); +0.09(d)	
2	Aequitas Neo-N	Canada	Mar 27, 2015	Randomized 3 to 9 milliseconds			non-HFTs only	-0.15	+0.18	Displayed orders not protected by OPR*
3	TSX Alpha	Canada	Sep 21, 2015	Randomized 1 to 3 milliseconds		Post-Only of minimum size		-0.16	+0.14	Displayed orders not protected by OPR*
4	NYSE American	US	Jul 24, 2017	Fixed 350 microseconds	2			+0.00(l); +0.02(d)	+0.02	

Notes: Inverted venues, which adopt a taker-maker fee schedule, are marked in shaded boxes. OPR is the acronym for Order Protection Rule, meaning that orders must be executed by the venue that provides the best price available in the market; it is similar to the Rule 611 of Regulation NMS in the US.
Source: Aequitas NEO Exchange Inc., *Membership and Trading Fee Schedule*, Section 3.2, July 1, 2017, avaiable at *https://www.aequitasneo.com/documents/en/trading-data/NEO-Membp-and-Trading-Fee-Sched-July-1-2017.pdf*. TSX Alpha, *TSX Alpha Exchange Fee Schedule*, available at *https://www.tsx.com/trading/tsx-alpha-exchange/fee-schedule*.

(2017) assume the fundamental value of the representative asset follows a martingale, thus these analyses may be more relevant in a short time framework.

For working horse models like Grossman and Stiglitz (1980) and Glosten and Milgrom (1985), it is assumed that some traders have superior knowledge than the dealer or market maker *with certainty*. In modern trading scenario, this is tantamount to claiming that some HFTs are always right about a price movement of a stock, which but exists at best when the information traffic is normal, and a jump in the NBBO is sufficiently large to prompt the HFTs to trade. A more realistic situation is that HTFs may only be able to make an educated guess on an imminent NBBO change. In modelling parlance, they receive a noisy signal of an imminent change in the fundamental value of the asset: a quote may change with a high probability, yet not for sure. This incentivizes HFTs to engage in a "crumbling quote arbitrage" while motivates IEX to launch its crumbling quote signal (Wah et al., 2017; Bishop, 2017).[26]

Figure 3 highlights such statistical strategies IEX faces. In particular, we use τ_f to denote the latency of a direct feed, that is, the time it takes for a quote change in an outside market to transmit and be learned by IEX; τ_{HFT} is the latency of a typical HFT, which is smaller on average than τ_f. Figure 3 also illustrates a key difference between the stale quote and the crumbling quote signal arbitrages: the timing that an HFT chooses to submit market orders.

3.2. The First Layer of Delay

Given that the real trading environment is random and time-varying, we dispense with game-theoretical modelling that characterizes the strategic behavior between traders, and seeks a static or stationary solution. Instead, we take the perspective of IEX itself, and discuss how to choose the optimal delay to minimize the time slot for adverse selection.

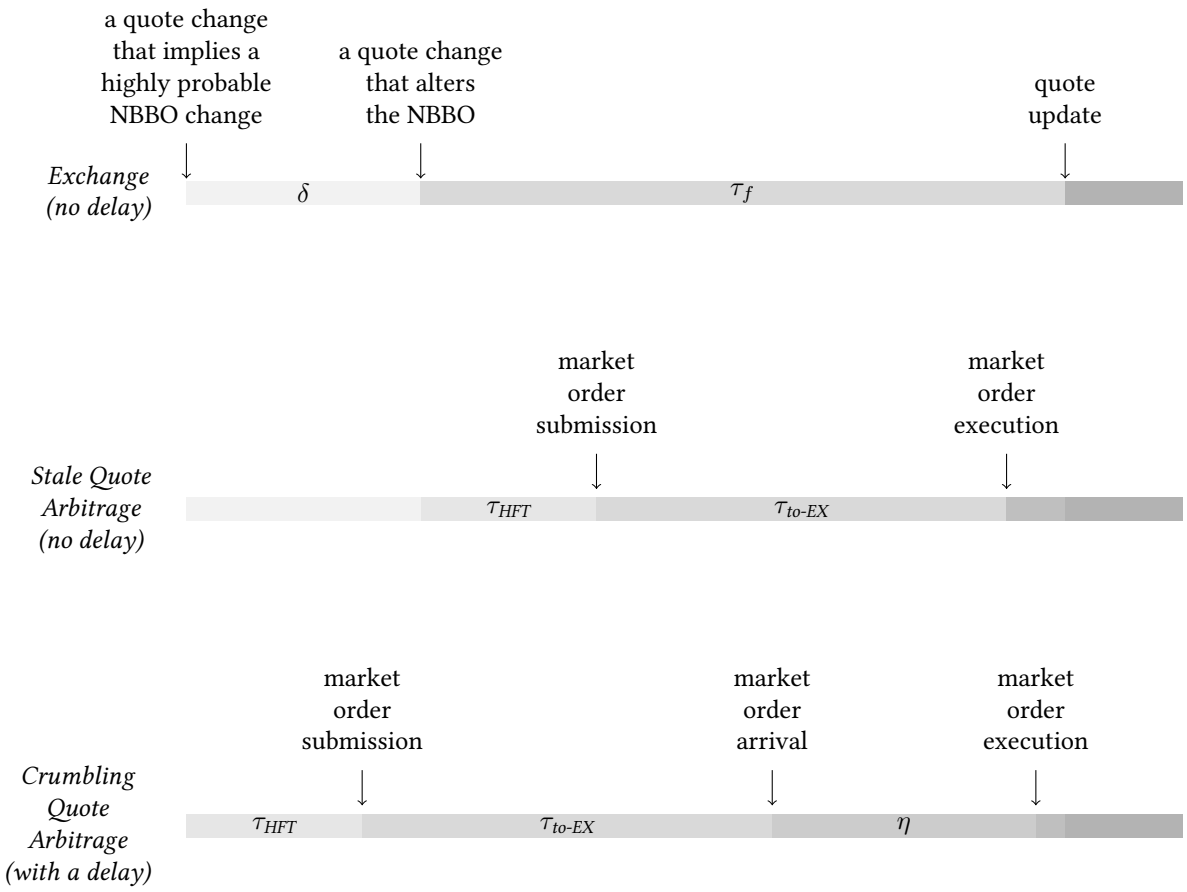
The first layer of delay, η, amounts to 350 microseconds; in this part, we will show that η is insufficient when HFTs arrive with a high intensity. We assume that the response time of IEX or the HFT can be taken as fixed, as it does not involve the long-distance transmission of information. Using letter f to denote "feed," we denote the time it takes the IEX to update its quote by τ_f and assume that τ_f follows a shifted exponential distribution with the following probability density function:

$$f_{\tau_f}(x) = \lambda_f e^{-\lambda_f (x-\tau_{f0})}, \qquad x > \tau_{f0}, \tag{1}$$

where τ_{f0} is an intrinsic delay for IEX to receive, compute its NBBO and reprice the pegged orders, which serves as the lower bound for τ_f; λ_f is a rate parameter. This assumption on latency distribution follows from Staddon (2016, p. 45). We can further impose that the order submission intensity triggered by a change in the NBBO is different for different stocks; this follows from Chao, Yao, and Ye (2017), where it is found that lower-priced stocks attracts more high-frequency trading. A resting M-Peg order can be adversely selected when it trades against a market order that arrives right before the exchange updates the NBBO. The latency for this market order m is

$$\tau_m^* = \tau_{HFT} + \tau_{to\text{-}EX}, \tag{2}$$

[26] IEX began to charge a Crumbling Quote Remove Fee from January 1, 2018. This is an access fee on investors who take liquidity when the signal is on (the quote is unstable), and the volume taken exceeds a certain limit. See IEX, "New FIX Tag Values and Launch of the Crumbling Quote Remove Fee", *IEX Trading Alert #2017 - 043*, October 19, 2017; available at *https://iextrading.com/trading/alerts/2017/043/*.



Notes: τ_{HFT} is the intrinsic latency (response time) of a typical high-frequency trader, τ_f is the latency that IEX receives the quote change signal and determines to update its quote. η is the first layer of delay applied to all eligible orders; δ is the second layer of delay that is contingent on a highly possible NBBO change. For illustration purpose, we don't draw the graphs in terms of their actual time scale.

Figure 3: Stale Quote Arbitrage and Crumbling Quote Arbitrage

where τ_{HFT} is the internal response delay of a typical high-frequency trader, and we assume it to be fixed; $\tau_{to\text{-}EX}$ is the transmission time it takes for a market order to arrive at the exchange, which is comprised of a fixed component and a random one. Then, we use a shifted exponential distribution to model τ_m^*:

$$f_{\tau_m}(y) = \lambda_m e^{-\lambda_m(y-\tau_{m0})}, \qquad y > \tau_{m0}, \tag{3}$$

where λ_m is a rate parameter, and τ_{m0} is the summation of τ_{HFT} and the fixed component of $\tau_{to\text{-}EX}$. With the first layer of delay η, the new latency for HFTs becomes

$$\tau_m = \tau_m^* + \eta$$

which follows another shifted exponential distribution:

$$f_{\tau_m}(y) = \lambda_m e^{-\lambda_m(y-\tau_{m0}-\eta)}, \qquad y > \tau_{m0} + \eta. \tag{4}$$

To assess the performance of the first layer of delay, we want to compute the probability that a resting order is adversely selected—that is, the chance that a market order arrives *before* the quote

change, i.e., $\tau_f > \tau_m$. The following expression presents this probability:

$$\begin{aligned}
\Pr\{\tau_f > \tau_m\} &= \int_{\tau_{m0}+\eta}^{\infty} \int_{\max\{y,\tau_{f0}\}}^{\infty} f_{\tau_f,\tau_m}(x,y)\mathrm{d}x\mathrm{d}y \\
&= \int_{\tau_{m0}+\eta}^{\infty} \int_{\max\{y,\tau_{f0}\}}^{\infty} \lambda_f e^{-\lambda_f(x-\tau_{f0})} \quad \lambda_m e^{-\lambda_m(y-\tau_{m0}-\eta)}\mathrm{d}x\mathrm{d}y \\
&= \begin{cases} \frac{\lambda_m}{\lambda_m+\lambda_f} e^{-\lambda_f \tau_{mf}} & \tau_{mf} \quad 0 \\ 1 \quad \frac{\lambda_f}{\lambda_m+\lambda_f} e^{\lambda_m \tau_{mf}} & \tau_{mf} < 0 \end{cases},
\end{aligned}$$

where $\tau_{mf} = \tau_{m0} + \eta \quad \tau_{f0}$ represents the intrinsic difference in delay.

According to the first line of the expression above, the probability of adverse selection is decreasing in η. This is because the integrand, which is the joint probability density function of τ_f and τ_m, is strictly positive and η only appears in the lower limit of the integration. The decreasing relationship explains why adopting the first layer of delay effectively reduces adverse selection.

The expression above for the probability of adverse selection is based on the assumption that the exchange and the HFT respond to the quote change that alters the NBBO simultaneously. However, the reality is, as we have mentioned earlier, that speculative traders usually develop proprietary models to predict any potential change in the NBBO. This enables HFTs to respond to a signal of a highly probable quote change before the exchange responds to the exact signal. The early action of HFTs counteracts the fixed delay added by the exchange, and we term it as δ (see the upper and lower panels of Figure 3). So timing starting from the precedent predictive signal, the new set of latencies becomes $\delta + \tau_f$ for the exchange, and remains equal to τ_m for the HFTs. The new intrinsic difference is therefore

$$\tau_{mf} \quad \delta.$$

To counteract the effect of δ, the exchange should extend the delay for HFTs. But the predictive model of HFTs usually predicts a potential change in NBBO ahead of a much longer time (typically on the order of a millisecond) compared with η. It is therefore unrealistic to further extend the first layer of delay to cater for those prediction models.

3.3. The Second Layer of Delay

To minimize this second type of arbitrage, the key is to determine δ, the time length between a highly probable signal and an exact quote change. Without loss of generality, we only present the results for the best offer of a liquid stock, and the reasoning for the best bid can be derived analogously. Given that the majority of liquidity on IEX is non-displayed and their pricing depends on the NBBO, we ignore the case that IEX itself establishes the NBBO.

Since the US equity market is fragmented, not every quote change eventually leads to an NBB or NBO change, and absolute quote change intensity is different for different stocks; for example, Hasbrouck (2017) finds that for 150 stocks listed on NYSE, AMEX (now NYSE America), and NASDAQ, the number of quotes for stocks in the smallest to largest quintiles ranges from 1,000 to 180,000, while the number of NBO or NBB changes ranges only from 100 to 4,000. But the ratio of quote changes to NBB/NBO changes seems to be stable: referring to Hasbrouck (2017), if the quote changes are split evenly between bids and offers, then approximately every 5 bid (ask) changes lead to one change in the NBB (NBO).

In fact, an NBO change is the joint outcome of multiple quote changes from all major exchanges. Yet not all exchanges are equally important. For the crumbling signal adopted since April 2017,

IEX focuses on only the top eight exchange in terms of market share, namely, NYSE, NYSE Arca, NASDAQ, NASDAQ BX, BYX, BZX, EDGA, and EDGX. Suppose the probability that an exchange first exhausts its top-of-book liquidity within one unit of time is p, then the probability that n exchanges crumbles into a new price follows[27]

$$q_n = \Pr\{n \text{ exchanges crumble}\} = \frac{N!}{(N-n)!\,n!}\, p^n(1-p)^{N-n}$$

The exchange must maximize the accuracy of the alternative signal; say, it must find the best cutoff number of exchanges, n, such that the probability of finally landed with a NBO change conditional on finding $n < N$ quote change is largest

$$\begin{aligned} q_{N|n} &= \Pr\{N \text{ exchanges crumble} \mid n \text{ exchanges crumble}\} \\ &= \frac{\Pr\{\text{all } N \text{ exchanges crumble}\}}{\Pr\{n \text{ exchanges crumble}\}} \\ &= \frac{(N-n)!\,n!}{N!}\left(\frac{p}{1-p}\right)^{N-n} \end{aligned} \tag{5}$$

where the second equality entails from our independence assumption. Denote k as the number of bid quote changes in one of the N exchanges within a unit of time, and it follows a Poisson distribution with intensity λ, then the waiting time to observe the next NBBO change τ, therefore, follows an exponential distribution with intensity $q_n N\lambda$.

Also, by the same independence assumption, suppose the number of quote change in every exchange follows a Poisson distribution with intensity λ, then joint cumulative distribution function of the waiting time of n exchanges crumble τ_n and an NBO change τ_N after that is

$$f(\tau_N \mid \tau_n,\, n) = \lambda_{N|n}\; e^{-\lambda_{Njn}(\tau_N - \tau_n)}$$

where $\lambda_{N|n} = q_{N|n}(N-n)$; then τ_N follows the following distribution

$$\begin{aligned} f(\tau_N \mid n) &= \int_0^{\tau_N} f(\tau_N \mid \tau_n,\, n) f(\tau_n \mid n)\mathrm{d}\tau_n \\ &= \int_0^{\tau_N} \lambda_n\; \lambda_{N|n}\; e^{-(\lambda_n - \lambda_{Njn})\tau_n}\; e^{-\lambda_{Njn}\tau_N}\mathrm{d}\tau_n \\ &= \frac{\lambda_n\; \lambda_{N|n}}{\lambda_{N|n}\;\; \lambda_n}\left(e^{-\lambda_n\tau_N} - e^{-\lambda_{Njn}\tau_N}\right) \end{aligned} \tag{6}$$

where $f(\tau_n \mid n) = \lambda_n e^{-\lambda_n\tau_n}$ with $\lambda_n = q_n n\lambda$. Note that the above density is conditional on the assumption that the quote is not an exact change in NBO such that $n \neq N$ thus λ_{N-n} is well-defined. If not, then there is an additional mass of $\lambda_N = q_N N\lambda$ at $\tau_N = 0$. Since $\delta < \tau_M$, the additional layer of delay can be determined by looking for a cutoff value τ_N such that $\Pr\{\tau_N - \tau_N\}$ approaches 1, say, 99%.

[27] The independence assumption can be relaxed by imposing a correlation structure on the Binomial distribution; but we don't pursue it here for the sake of tractability.

3.4. *Calibration*

In reality, it is inefficient to use a time grid that is too tiny—events can become sparse on a fine grid, rending estimation to be poor. As a result, we set the minimum accuracy or the smallest time slot to 10 microseconds.

We set τ_{0f}, the intrinsic delay of IEX, to be 270 microseconds; the random part is specified as $\lambda_f = 10$, which implies $\Pr\{\tau_f \quad 300\} > 99\%$; that is, IEX can respond within 300 microseconds with a probability of 99% over all occurrences. Similarly, we set the intrinsic latency of a market order at $\tau_{0m} = 100$, and the random part to be $\lambda_m = 10$. Accordingly, $\Pr\{\tau_f > \tau_m \mid \tau_{fm} \quad 0\}$, the probability that an HFT's response is faster than the exchange, is less than 5%.

In equation (5), the conditional probability $q_{N|n}$ is largest when $n = N \quad 1$, which verifies that in an earlier version of the Signal where a contingency table approach is applied, IEX predicts a bid change only when "the number of bids had dwindled all the way down to 1" (Bishop, 2017, p. 21). To get the density of τ_N conditional on n, that is, the density of the time elapsed between observing 7 exchanges crumbles and all exchanges move to the new NBBO, we set $p = 0.2$, and $\lambda = 10$. The result is shown in Figure 4; we can see that the density of τ_N conditional on observing n exchanges crumbles to a new price, as specified in equation (6), is not monotone. For our specification of parameters, we can see that a cut-off at around 2 milliseconds can deliver us to a likelihood of zero. This explains why the prediction or firing window are set to 2 milliseconds.

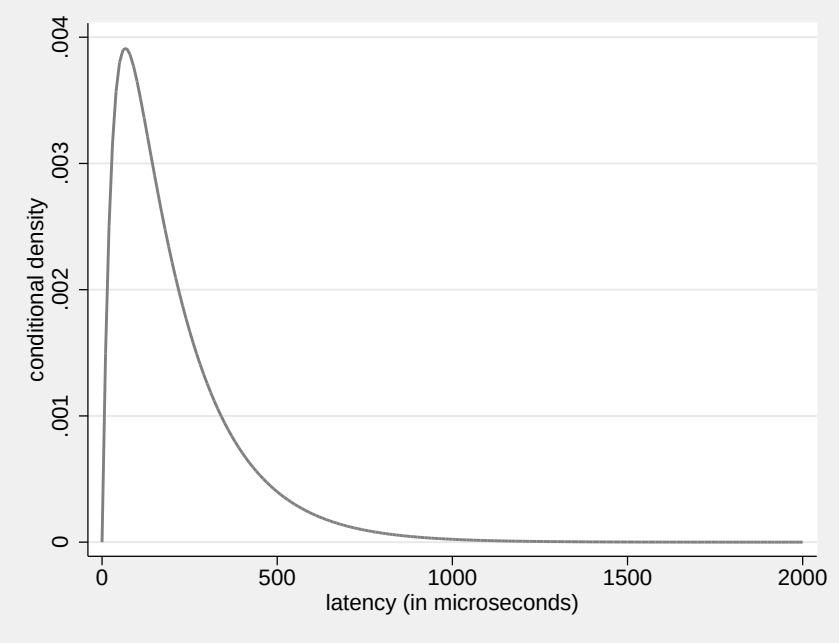


Figure 4: The Density of the Time Elapsed Between Observing 7 Exchanges Crumbles and All 8 Exchanges Move to a New Price

Notes: The horizontal axis is the latency τ_N, measured in microseconds; the calculations are based on $N = 8$ and $n = 7$. Note that the conditional density is in fact a likelihood function, so the area under the density curve does not sum to one.

3.5. *Implications*

From Section 2, we know that different order types enjoy different degrees of protection from adverse selection. Specifically, lit orders are not protected; the M-Peg orders, while protected by

the 350-microsecond delay, are not protected by the crumbling quote signal. As a result, they are more likely to be sniped than primary and discretionary pegs that are protected by both layers of delay. The joint outcome on adverse selection, therefore, may depend on proportions of these orders and the intensity of the trading activities.

Moreover, there is a statistical difficulty in implementing the Crumbling Quote Signal: the validity of the Signal impinges on the successful prediction of a NBBO change, which can be an event of low probability. In particular, for large stocks whose trading is more active than the medium- and small-sized stocks, a top-of-book quote change in a single venue is less likely to be decisive in generating a new NBBO. Referring to our explanatory model, a lower p (the proportion that a quote sets a new NBBO) and a larger λ (the quote change intensity) might result in a flatter, fatter tailed conditional likelihood than what is shown in 4, therefore higher false negatives; that is, failure to predict an NBBO change when it actually takes place soon after.

Consequently, we expect the adverse selection problem to be rectified more in the small- and medium-sized groups. We notice that this limitation of the Signal might be one of the drivers that prompts IEX to charge a Crumbling Quote Remove Fee to further detain possible crumbling quote arbitrages.

4. Data

To test the predictions from the models, we restrict our sample to 56 trading days from January 3 to March 23, 2017; we discard the observations in late March because IEX phased in a new version of crumbling quote signal from March 24 to 28, 2017; also, a modification to the trading rule of Primary Peg Orders and Discretionary Peg Orders was carried out during March 27 to April 3, 2017. For the moment, to make a comparison with Wah et al. (2017), we employ the latest daily Trade and Quotes (DTAQ) data, which is microsecond-stamped for NYSE listed stocks during our sampling period, and nanosecond-stamped for NASDAQ stocks.

Throughout the rest of this paper, we denote P_t as the trade price, B_t as the bid price, A_t as the ask price, M_t as the midpoint, which is the average of national best bid (NBB) and national best offer (NBO), $S_t = A_t \quad B_t$ is the quoted spread. Furthermore, let P_s, $s < t$ be the last trade such that $P_s \neq P_t$, and NBB_t and NBO_t; the midpoint is defined as the arithmetic average of NBB and NBO, say $M_t = (NBB_t + NBO_t)/2$. For simplicity in notations, we suppress the subscript i that indexes individual stocks.

4.1. Sample

The 120-Stock Data Set. Instead of using all symbols, we only consider a representative set of tickers named the NASDAQ HFT data set; see Brogaard (2010, 2012); Brogaard, Hendershott, and Riordan (2014) and Subrahmanyam and Zheng (2016) for a full description. The original data set includes 120 firms, with 40 stocks in each of the large, medium, and small capitalization groups. However, observations of some sample stocks are no longer available due to a spin-off, merger or acquisition (M&A), or delisting before our sampling period. As a result, we delete the delisted stocks or when there is an M&A, and replace an old ticker with the new one in the case of a pure name change. Our final sample contains 36, 30, and 31 stocks for the three size groups, are given in section 1 of Appendix A; modifications to the original list of tickers are shown in Table A.12. For the sake of simplicity, we still refer to the surviving sample as the "120-Stock Data Set".

Dow 30 Companies. Our statistical model predicts that the speed bump would perform better in small- and medium sized groups. However, the 120-Stock Data Set seems to be unbalanced in terms of price: since NYSE only trades Tape A stocks there, its average price of the selected sample is much lower than the other venues. To remedy this sample selection problem, we use the Dow 30 companies as an alternative. These companies represents the most actively traded large caps in the U.S. equity market. This sample is also examined by Bartlett and McCrary (2017), but we only look at the NYSE-listed companies.

4.2. Trade Directions

In IEX's white paper, the trade direction is computed "from the perspective of the liquidity adder"; that is, the trade is a "buy" if P_t M_t and a "sell" if $P_t > M_t$. Furthermore, ignorant of the tick rule, when calculating the markouts and realized spreads, Wah et al. (2017) discards all trades within the spreads and restricts its scope to "executions at the NBB or NBO", which essentially evokes the Quote Rule only.[28]

In contrast, the academic literature has provided with us different algorithms to determine trade directions. Using non-TAQ data sets from which the buy-sell indicator D_t can be inferred, these methods were proved to have high accuracy. For example, Odders-White (2000) argue that Lee-Ready algorithm correctly classifies 85% of the TORQ data, which include 144 NYSE stocks from November 1990 to January 1991. In addition, Ellis, Michaely, and O'Hara (2000) focus on the NASD data sets with 313 NASDAQ stocks from 1996 to 1997, and find that the Lee-Ready approach is less accurate in signing trades inside the spreads, and has proposed an alternative method (EMO). Chakrabarty, Li, Nguyen, and Van Ness (2007) (CLNV) is yet another alternative to the Lee-Ready approach. Based on the post-decimalization trades from INET (acquired by NASDAQ later), the CLNV approach is shown to have marginally improved the overall accuracy of LR and EMO on the ITCH data from April to June 2005, and is more precise in signing trades inside the spreads.

These algorithms, in fact, share the same tick rule but differ in trade rules to determine trade directions:

- Lee and Ready (1991). Quote Rule: the trade is a buy (buyer-initiated) if $P_t > M_t$, and a sell (seller-initiated) if $P_t < M_t$; and is also called the Trade Rule. Tick Rule: when $P_t = M_t$, the trade is a buy if P_t is an upward tick, say, $P_t > P_s$ with $s < t$; it is a sell if P_t is a downward tick, say, $P_t < P_s$.
- Ellis, Michaely, and O'Hara (2000). Quote Rule: the trade is a buy if $P_t = NBO_t$, and a sell if $P_t = NBB_t$. Tick Rule: when the trade rule cannot determine the trade direction, apply the tick rule.
- Chakrabarty, Li, Nguyen, and Van Ness (2007). Quote Rule: the trade is a buy if $0.3NBB_t + 0.7NBO_t$ P_t NBO_t, and a sell if NBB_t P_t $0.7NBB_t + 0.3NBO_t$. Tick Rule: when the trade rule cannot determine the trade direction, apply the tick rule.

Pöppe, Moos, and Schiereck (2016) have surveyed existing literature on the efficacy of these algorithms and find only minor differences. Similarly, we expect that these methods to generate comparable results. However, given our choice of a 15-second interval, the sign on the adverse

[28] These treatments can be found on page 49 of Wah et al. (2017), where *Query 1: Core Trades* classifies a buy when price<= mid; and the codes to retain trades only at NBBO is in the last part of *Query 5: Markouts*, on page 52.

selection measures using EMO and in particular CLNV can go negative for large stocks. This finding is understandable: some large stocks are often tick-constrained, therefore, it is rare that trades occur within the spread aside from the midpoint; as a result, it is the tick rule that we always evoke to determine the trade direction. And according to , the rule alone has proved the least accurate compared with LR and EMO on various data sets.

Nevertheless, given that IEX has substantial liquidity at the midpoint, it is expected that the directions of trades in IEX are determined by the tick rule more often than other venues. It is not clear whether IEX's trades, which happens at the midpoint more than its counterparts, affect these trade direction algorithms or not. Moreover, without more detailed data sets that contain the trade direction, we are agnostic about the validity of these methods in the now fast-moving market environment.

4.3. Summary Statistics

To provide an overview of the market, we compute some summary statistics for the selected tickers. Specifically, we are interested in the following measures: (1) the number of NBBO updates; (2) the number of trades; (3) trading volume in shares; (4) average trade size in shares, defined as the total trading volume divided by the total number of trades; (5) average price; (6) volatility, calculated as the difference between the high and low price, then divided by the average price. For a specific exchange, to suppress the effect of sparse trading, we discard its daily average measures whenever the total number of trades of that day is under 5. Also, we set the volatility to missing if the maximum trade price equals the minimum. After that, the panel of measures are averaged over the selected tickers and trading days.

The 120-Stock Data Set. The results presented in Table 4 justify why IEX chooses the top eight exchanges to obtain a set of explanatory variables that are predictive of an NBB or NBO change. We can see that NYSE and NASDAQ have the largest number of NBBO updates, trades, and the highest trading volumes; NYSE Arca, NASDAQ, NASDAQ BX, BYX, BZX, EDGA, and EDGX are the next six active venues; NASDAQ PSX, with a unique Price Setter Pro Rata model to allocate incoming orders by a price-size-display priority rule, enjoys a smaller trading volume that is less than not only the top eight, but also the IEX.[29]

In addition, stocks in different size groups exhibit different patterns across different exchanges. For large-cap stocks, the three inverted venues—NASDAQ BX, BYX, EDGA—have much more trades than NBBO updates, because liquidity takers can trade there first and receive a rebate before paying a fee to exhaust the liquidity at the prevailing NBBO elsewhere. But for the other two size groups, this pattern only holds for EDGA in the medium-cap cohort, where 53 NBBO updates are contrasted with 109 trades.

In terms of trade size, all the inverted exchanges have a measure below 100 shares, which implies a nontrivial proportion of odd-lot trades in spite of the size. For NASDAQ PSX, because under the same price, orders that establish the best price will have 40% of orders executed against the incoming order, and the unfilled part, together with other lit orders in the same [30] In the medium-sized

[29]The market share of NASDAQ PSX is less than 1% according to the statistics provided by Cboe; available at *https://markets.cboe.com/us/equities/market_share/market/*. The business model of NASDAQ PSX encourage investors to post large, displayed orders and set the best price on PSX, and the pro rata allocation would round shares in lots; see *http://www.nasdaqtrader.com/Trader.aspx?id=nasdaqpsx*.

[30]In fact, using the NASDAQ Historical TotalView ITCH data in 2013, Johnson, Van Ness, and Van Ness (2017) find

groups, only NYSE and IEX have an average trade size larger than 100; this result is consistent with Wah et al. (2017), where it is found that IEX ranks the second in its proportion of block volume in Tape A and B stocks, and ranks first in Tape C stocks.[31] But because of NYSE's practice of bunching orders, the over-one-lot average trade size NYSE enjoys across the three size groups may not be of much meaning.[32]

As for the average price, IEX's volatility and average price are of the same magnitude of the inverted exchanges; this may be ascribed to its rich liquidity at the midpoint, thus less exposure to a bid-ask bounce. At the same time, stocks traded in NYSE seem to be cheaper than other exchanges. However, it arises from that NYSE trades Tape A stocks exclusively; as a result, the measure ignores high-priced stocks that are traded in NASDAQ thus in Tape C, e.g. Amazon, the prices of which exceed $750. In the medium-size stocks group, IEX's volatility is lower than the big eight; although NASDAQ PSX owns the lowest volatility, this may arise from its sparse trading. In the small-cap group, with an average volatility of 3.367%, IEX loses only to the best performer, NASDAQ PSX.

Dow 30 Companies. We now turn to look at the 26 NYSE-listed stocks in the Dow 30 Companies, and the summary statistics are shown in Table 5. Similar to our results for the 120-Stock Data Set, for the three inverted venues (NASDAQ BX, BYX, and EDGA), the number of trades far exceeds the number of NBBO updates. For our selection of tickers, NYSE has the highest volatility but the lowest average price. For IEX, its ratio of NBBO updates to trades seems more consistent with the inverted exchanges. In terms of average trade size, IEX ranks the second and only loses to NYSE; again, this might be owing to NYSE's bundling of small trades.

5. Measures of Adverse Selection

5.1. Adverse Selection

We first use the conventional measure on adverse selection (or price impact), defined as follows

$$\textit{Adverse Selection}_t = D_t \quad \frac{M_{t+\tau} \quad M_t}{M_t} \tag{7}$$

where D_t is +1 for buyer-initiated trades, 1 for seller-initiated trades; M_t is the midpoint; τ is some time interval; the subscript t indexes the clock time when the trade takes place. While it was customary to choose $\tau = 300$ seconds, see Hendershott, Jones, and Menkveld (2011) for an example, the latency reduction in modern markets justifies a choice of τ around 15 seconds. To assess the performance for major venues, we compute this *Adverse Selection* measure for each stock, and weight it by exchange-wide total dollar trading volumes (either in shares or dollar trading volume), and then take averages over all selected stocks and all trading days. Since the magnitude of the measure is small, we multiply the raw numbers by 100.

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that among their sample of 1,400 NASDAQ stocks, almost 1/3 of all trades are in odd-lots.

[31] A block trade, as defined in Wah et al. (2017), is a trade that involves 10,000 shares or $200,000 in value.

[32] When one large order is matched and transacted against several small orders, NYSE reports the size of the trade as that of the single large order, thus underestimates the number of odd-lot trades in NYSE. After being criticized by IEX for such practice, NYSE issues a trade entry for each small orders but only to clients who purchase the more expensive proprietary data feed; the TAQ still records the bunched size. See John McCrank, "NYSE plan to update private data feed draws criticism from IEX," *Reuters Business News*, August 20, 2015; available at *https://www.reuters.com/article/us-interconti-exc-nyse-data-iex/nyse-plan-to-update-private-data-feed-draws-criticism-from-iex-idUSKCN0QP2CE20150820*.

Table 4: Summary Statistics (Daily Average, 120-Stock Data Set)

Panel A: Large Stocks

Stock Exchange	#N NBBO Updates	#N Trades	Trading Volume (#Shares)	Trade Size (#Shares)	Volatility (%)	Average Price
NYSE	86,822	3,959	1,142,526	277	1.502	68.471
NYSE Arca	7,481	3,051	395,704	119	1.413	128.755
NASDAQ	40,597	7,819	922,647	109	1.438	128.753
NASDAQ BX	318	1,872	204,189	92	1.392	128.758
NASDAQ PSX	2,206	585	76,358	106	1.326	128.747
BYX	362	3,066	364,075	91	1.406	128.756
BYZ	4,966	3,643	441,180	103	1.421	128.753
EDGA	153	1,583	181,085	96	1.365	128.761
EDGX	4,649	3,244	429,751	117	1.408	128.753
IEX	739	1,050	188,496	155	1.358	128.752

Panel B: Medium Stocks

Stock Exchange	#N NBBO Updates	#N Trades	Trading Volume (#Shares)	Trade Size (#Shares)	Volatility (%)	Average Price
NYSE	4,710	761	81,103	133	1.799	79.134
NYSE Arca	759	380	36,079	99	1.579	74.759
NASDAQ	5,197	1,115	90,760	87	1.734	74.570
NASDAQ BX	285	252	21,107	75	1.622	74.576
NASDAQ PSX	334	44	4,671	86	1.214	76.093
BYX	656	309	26,344	77	1.666	74.577
BYZ	450	292	29,775	91	1.546	74.571
EDGA	53	109	10,898	87	1.360	74.934
EDGX	342	267	27,346	97	1.515	74.690
IEX	147	108	15,674	126	1.406	74.407

Panel C: Small Stocks

Stock Exchange	#N NBBO Updates	#N Trades	Trading Volume (#Shares)	Trade Size (#Shares)	Volatility (%)	Average Price
NYSE	3,094	260	30,709	119	2.373	38.413
NYSE Arca	335	173	18,013	92	2.401	29.083
NASDAQ	4,217	627	69,222	92	2.692	29.260
NASDAQ BX	234	158	13,567	76	2.483	29.149
NASDAQ PSX	138	31	3,438	89	1.902	28.047
BYX	483	186	16,314	77	2.582	29.260
BYZ	271	160	17,194	92	2.330	29.235
EDGA	53	68	6,877	86	2.099	29.121
EDGX	274	172	21,938	100	2.306	29.176
IEX	34	58	8,757	125	2.028	28.996

Notes: Inverted venues, which adopt a taker-maker fee schedule during our sampling period, are marked in shade. The trades in NYSE MKT (now NYSE American), NYSE National and Chicago Stock Exchange are excluded because of no or sparse trading. The sample stocks are the survived tickers from the frequently used 120-stock HFT Dataset. The subsample for large stocks in this data set, however, is unbalanced because NYSE-listed stock may be underrepresented.

Table 5: Summary Statistics (Daily Average, 26 NYSE-listed Dow 30 Companies)

Stock Exchange	#N NBBO Updates	#N Trades	Trading Volume (#Shares)	Trade Size (#Shares)	Volatility (%)	Average Price
NYSE	89,498	5,282	1,187,945	219	1.055	100.152
NYSE Arca	5,753	3,506	436,436	116	1.040	100.153
NASDAQ	15,208	6,525	675,091	99	1.048	100.154
NASDAQ BX	370	1,798	179,625	88	1.027	100.156
NASDAQ PSX	1,036	401	45,836	101	0.968	100.154
BYX	305	2,680	283,715	84	1.029	100.160
BYZ	3,964	3,904	423,565	97	1.041	100.154
EDGA	172	1,537	164,831	93	1.007	100.158
EDGX	2,559	3,041	371,695	112	1.037	100.152
IEX	514	1,040	173,642	147	1.011	100.155

Notes: Inverted venues, which adopt a taker-maker fee schedule during our sampling period, are marked in shade. The trades in NYSE MKT (now NYSE American), NYSE National and Chicago Stock Exchange are excluded because of no or sparse trading. The sample stocks are the 26 NYSE-listed stocks from the Dow 30 Companies.

5.2. *Midquote Stability*

Wah et al. (2017) adopt an alternative measure on adverse selection, calculated as the percentage of trading volume happened when the midpoint is stable; that is, the the midpoint at $t + \tau$ remains at the level it was τ seconds earlier:

$$\textit{Midpoint Stability} = \frac{\sum_t \textit{Trading Volume}_t \quad \mathit{I}\,\mathit{f} M_{t+\tau} = M_t \mathit{g}}{\sum_t \textit{Trading Volume}_t} \quad 100\% \tag{8}$$

where t indicates the clock time when the trade happens; $\mathit{I}\,\mathit{f} M_{t+\tau} = M_t \mathit{g}$ is an indicator function that takes one if $M_{t+\tau}$ remains at M_t, and zero otherwise. Also, we use both share and dollar trading volume. This definition ignores the case that the midpoint may change its value between t and $t + \tau$, yet the final value at $t + \tau$ reverts back to its starting level at t. Despite this disadvantage, the merit of the measure is, it does not require a trade direction indicator.

5.3. *Realized Spread Based on Queue Lengths*

Wah and Feldman (2017) propose another measure for adverse selection, which is essentially a daily, exchange-wise realized spread (or trade markout) based on the queue length; however, this measure is only applicable to trades that take place at the NBBOs. At a given exchange for a given stock in a given day, the measure is calculated as follows. (1) Link each trade at NBB or NBO with the corresponding market-wide depth (in shares), that is, the quoted size aggregated across all exchanges when the trade occurs. (2) Sort trades by their market-wide depths, from the deepest to the shallowest, whereby we arrange the trade into $q_{(1)}, q_{(2)}, \ldots, q_{(K)}$. (3) Let $Q = \sum_{k=1}^{K} q_{(k)}$ be the total trades, divide Q into 10 equal-volume buckets (each with size $Q/10$), and fill each bucket with the ordered trades consecutively, as long as after adding this trade the bucket is not or exactly filled; otherwise, the trade is passed to the next bucket.[33] (4) Calculate the realized spread for each

[33] This resembles the procedure in calculating the VPIN of Easley, López de Prado, and O'Hara (2012), only that in Wah and Feldman (2017) a trade cannot straddle two buckets, and the bucket size is determined on a daily basis, rather than the historical average.

bucket

$$\textit{Realized Spread} = D_t \quad \frac{P_t \quad M_{t+\tau}}{M_t} \tag{9}$$

where t is the time that trade k takes place. Then take average over different symbols executed in the exchange. As for the interval τ, Wah and Feldman (2017) uses 60 seconds.

The 120-Stock Data Set. The results for the two adverse selection measures are shown in Table 6, where again, the three size groups come up with different patterns. In the large-cap group, even under the same weight, different trade direction algorithms yield vastly different numerical values. In particular, measures computed from the Ready (LR) approach seems to be more consistent in the ranking with the Ellis, Michaely, and O'Hara (EMO) approach; but the Chakrabarty, Li, Nguyen and Van Ness (CLNV) does not confrom with the ranking of LR or EMP. For our choice of large stocks, when weighted by the number of shares and using the Lee-Ready approach, IEX does not perform the best, yet it still outshines 4 of the 7 maker-taker exchanges. This outcome is probable caused by some small trades with large unfavorable price, since when we use the dollar weighted measure, IEX ranks the third, only losing to two of the three inverted exchanges, NASDAQ BX and BYX, and is even better than EDGA. The results on Midpoint Stability also corroborate this finding: using either share or dollar weighting, IEX's percentage of stable quotes is lower than the NASDAQ BX and BYX, but is higher than EDGA.

For the two remaining groups, we can see from Panel B and C of Table 6 that IEX has the highest proportions of stable midquotes, which are above 38% and 50% for the medium- and small-caps, respectively. Referring to the Adverse Selection measures, NASDAQ PSX seems perform better than IEX if we use the share weighting; this might arise from the fact that NASDAQ PSX trades more shares in Tape B and C stocks than the more volatile Tape A stocks. Nevertheless, when we use dollar weighing, IEX has the lowest Adverse Selection in the medium-cap throughout; for small-caps, IEX has the lowest Adverse Selection when we adopt the EMO algorithms, and it only loses to EDGX when we use LR or CLNV algorithms. The favor of EDGX for small stocks might be ascribed to its rich liquidity for small stocks—in Panel C of Table 4, we can see that the trading volume of EDGX ranks the third and only comes after NYSE and NASDAQ.

Dow 30 Companies. The results on adverse selection and midpoint stability for the 26 NYSE-listed Dow 30 Companies are shown in Table 7. Again, no matter what weights we apply, there agreement that IEX excels in the adverse selection measure; interestingly, NASDAQ PSX . But when we look at the midpoint stability shown in the last two columns, we found that IEX is lagged behind the two of the three inverted exchanges.

5.4. Interval for Evaluation Revisited

For the moment, there is no universally agreed rule as for how to choose the interval τ. But the baseline is, it should be longer that the reporting delay, which is the difference between the timestamp that IEX records a trade in its own system, and the timestamp that IEX's trade is recorded in the SIP.

We have seen in the previous section that the adverse selection measure does not always agree with the midpoint stability measure, especially in large stocks. While the adverse selection is one reason why the bid-ask spreads exist and should be positive in general, the midpoint may embrace richer dynamics: in a fast-moving, yet fragmented market, a trade may not necessarily move the

Table 6: Measures of Adverse Selection (15 seconds, 120-Stock Data Set)

Panel A: Large Stocks

	Adverse Selection						Midpoint Stability	
Stock	(Share Weighted)			(Dollar Weighted)			(in Percentage)	
Exchange	LR	EMO	CLNV	LR	EMO	CLNV	#Shares	$Dollar
NYSE	0.0035	0.0035	0.0035	0.0035	0.0035	0.0035	25.8828	25.8826
NYSE Arca	0.0016	0.0016	0.0011	0.0011	0.0012	0.0012	18.8970	18.8975
NASDAQ	0.0033	0.0033	0.0023	0.0023	0.0025	0.0025	19.4849	19.4855
NASDAQ BX	0.0006	0.0006	0.0004	0.0004	0.0004	0.0004	35.0037	35.0043
NASDAQ PSX	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	20.3764	20.3768
BYX	0.0007	0.0007	0.0005	0.0005	0.0006	0.0006	35.3219	35.3226
BYZ	0.0012	0.0012	0.0010	0.0010	0.0010	0.0010	20.7856	20.7861
EDGA	0.0004	0.0004	0.0003	0.0003	0.0003	0.0003	31.0920	31.0926
EDGX	0.0013	0.0013	0.0010	0.0010	0.0011	0.0011	19.1000	19.1004
IEX	0.0003	0.0003	0.0001	0.0001	0.0001	0.0001	32.6859	32.6867

Panel B: Medium Stocks

	Adverse Selection						Midpoint Stability	
Stock	(Share Weighted)			(Dollar Weighted)			(in Percentage)	
Exchange	LR	EMO	CLNV	LR	EMO	CLNV	#Shares	$Dollar
NYSE	0.0089	0.0089	0.0082	0.0082	0.0088	0.0088	22.6706	22.6695
NYSE Arca	0.0032	0.0032	0.0030	0.0030	0.0032	0.0032	23.7621	23.7638
NASDAQ	0.0118	0.0118	0.0110	0.0110	0.0117	0.0117	24.0161	24.0176
NASDAQ BX	0.0028	0.0028	0.0026	0.0026	0.0027	0.0027	35.4199	35.4234
NASDAQ PSX	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	23.1500	23.1531
BYX	0.0032	0.0032	0.0029	0.0029	0.0032	0.0032	35.0794	35.0830
BYZ	0.0024	0.0024	0.0022	0.0022	0.0023	0.0023	25.1624	25.1637
EDGA	0.0008	0.0008	0.0007	0.0007	0.0008	0.0008	30.2037	30.2041
EDGX	0.0023	0.0023	0.0021	0.0021	0.0023	0.0023	24.2921	24.2968
IEX	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	38.6983	38.6999

Panel C: Small Stocks

	Adverse Selection						Midpoint Stability	
Stock	(Share Weighted)			(Dollar Weighted)			(in Percentage)	
Exchange	LR	EMO	CLNV	LR	EMO	CLNV	#Shares	$Dollar
NYSE	0.0184	0.0184	0.0165	0.0165	0.0183	0.0183	30.5178	30.5180
NYSE Arca	0.0043	0.0043	0.0041	0.0041	0.0043	0.0043	31.5110	31.5076
NASDAQ	0.0197	0.0197	0.0187	0.0187	0.0195	0.0195	30.0941	30.0935
NASDAQ BX	0.0039	0.0039	0.0038	0.0038	0.0038	0.0038	48.1219	48.1207
NASDAQ PSX	0.0008	0.0008	0.0008	0.0008	0.0008	0.0008	31.0570	31.0576
BYX	0.0053	0.0053	0.0050	0.0050	0.0053	0.0053	47.3371	47.3352
BYZ	0.0041	0.0041	0.0039	0.0039	0.0041	0.0041	31.9517	31.9491
EDGA	0.0016	0.0016	0.0016	0.0016	0.0016	0.0016	39.5391	39.5385
EDGX	0.0047	0.0047	0.0046	0.0046	0.0047	0.0047	30.1551	30.1524
IEX	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	49.7918	49.7892

Notes: Inverted venues, which adopt a taker-maker fee schedule during our sampling period, are marked in shade. The trades in NYSE MKT (now NYSE American), NYSE National and Chicago Stock Exchange are excluded because of no or sparse trading. To determine the trade direction, we use three approaches: Lee and Ready (1991) (LR), Ellis, Michaely, and O'Hara (2000) (EMO) and Chakrabarty, Li, Nguyen, and Van Ness (2007) (CLNV). The time interval τ taken to evaluate these measures is 15 seconds.

Table 7: Measures of Adverse Selection (15 seconds, 26 NYSE-listed Dow 30 Companies)

Panel A: Scaled Measure

	Adverse Selection						Midpoint Stability	
Stock	(Share Weighted)			(Dollar Weighted)			(in Percentage)	
Exchange	LR	EMO	CLNV	LR	EMO	CLNV	#Shares	$Dollar
NYSE	0.0020	0.0020	0.0020	0.0020	0.0020	0.0020	21.2313	21.2318
NYSE Arca	0.0008	0.0008	0.0008	0.0008	0.0008	0.0008	18.1102	18.1108
NASDAQ	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	18.8747	18.8752
NASDAQ BX	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	31.7823	31.7836
NASDAQ PSX	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	19.5107	19.5114
BYX	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	31.9416	31.9431
BYZ	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	20.1540	20.1546
EDGA	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	28.9267	28.9273
EDGX	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	18.3654	18.3658
IEX	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	30.1815	30.1826

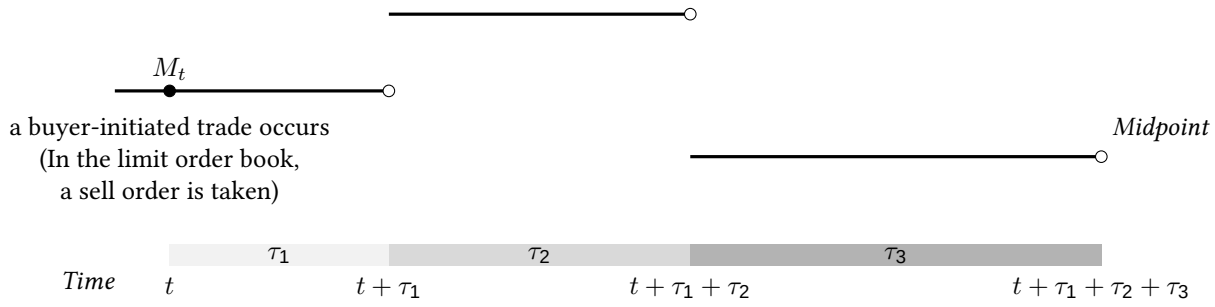
Notes: Inverted venues, which adopt a taker-maker fee schedule during our sampling period, are marked in shade. The trades in NYSE MKT (now NYSE American), NYSE National and Chicago Stock Exchange are excluded because of no or sparse trading. To determine the trade direction, we use three approaches: Lee and Ready (1991) (LR), Ellis, Michaely, and O'Hara (2000) (EMO) and Chakrabarty, Li, Nguyen, and Van Ness (2007) (CLNV). The time interval τ taken to evaluate these measures is 15 seconds.

NBBO, and the NBBO can change without trades. As a result, if the midquote experiences an U-shape or inverse U-shape swing, then whether the initiator of this trade is empirically considered as adversely selected or not, depends critically on how one chooses the time interval for evaluation.

To illustrate this point, Figure 5 provides an example where the midpoint remains the same for a while, then jumps to a higher level and stays there for a moment, only to experience a decline later and reverts to a level that is lower than the starting point, and keeps constant for some time. Consequently, if we choose to calculate the adverse selection before the jump, we will find nothing; if we evaluate the measure after the jump but before the slide, we will obtain positive adverse selection; if we evaluate the performance after the decline, we will come up with negative adverse selection. In other words, with an inappropriate interval choice, the disagreement of different trade direction algorithms may be amplified.

Given the current market condition—as Budish, Cramton, and Shim (2015) have commented, "industry observers remarked that 3 milliseconds is an 'eternity"'—a more reasonable choice might be of a magnitude of several milliseconds. Moreover, by the design of the speed bump, especially the crumbling quote signal, the critical time interval to assess its performance should be 1 to 10 milliseconds. As a result, we recalculate the the adverse selection measures using share weighting are shown in Table 8 and for the 120-stock data set and the Dow 30 companies, using the Lee-Ready approach only. No matter what time horizon we use, IEX outperforms other exchanges in the small- and medium-size group. But for the large-caps, NASDAQ PSX sometimes has lower adverse selection, this might be caused by the sparse trading and relatively low volatility there. Also, for the Dow 30 companies, at 1ms interval, IEX is at par with some inverted venues plus NASDAQ PSX. the results for dollar weighting are similar, and is presented in the appendix.

We also recalculate the midpoint stability measure on the interval of 1 milliseconds to 10 seconds, and report the results in Table 9. Using this trade direction-free approach, we can see that for the large caps in (Panel A) and Dow 30 companies (Panel D), IEX outperforms other exchanges



Notes: t is the calendar time when a trade takes place. To see if there is adverse selection, we must pick up a time interval τ. Consider three possibilities: (1) $\tau < \tau_1$, then the resting sell order is not adversely selected because the midpoint remains the same; (2) the midpoint increases after $t + \tau_1$, and if one chooses $\tau_1 < \tau$ $\tau_1 + \tau_2$ then the resting sell order is adversely selected—it could have sold at a higher price; (3) after $t + \tau_1 + \tau_2$ the midpoint drops below M_t, and if one chooses $t + \tau_1 + \tau_2 < \tau$ $t + \tau_1 + \tau_2 + \tau_3$, then the adverse selection measure is negative. For illustration purpose, we don't draw the graph according to the actual time scale.

Figure 5: Time Interval Choice and Adverse Selection—An Example

when the interval chosen is shorter than 5s. As before, IEX performs consistently better than others exchanges in small- and medium-sized stocks.

As shown in Panel A and D of Table 8, for large stocks, using the midpoint-scaled measure might underweight the adverse selection of these usually highly priced stocks, therefore understate the effect in the whole sample. To corroborate our results in Table 9, we further compute the unscaled midpoint stability, defined as

$$\textit{Adverse Selection}_t = D_t \quad (M_{t+\tau} \quad M_t)$$

we then weight each stocks by their share or dollar volume; and the share weighted results are shown in Table 10.

6. Conclusion and Discussions

Extant theoretical model has predicted IEX to reduce adverse selection, and empirically, IEX does perform well on small- and medium-sized stocks, and this result is robust to different choice of trade direction algorithms and different weighting. However, IEX does not excel always on the adverse selection measures as against other exchanges, especially with respect to large-cap stocks and when the interval for evaluation is more than 10 milliseconds. Of course, as IEX has been innovating its mechanism, to further validate our results, we may need to look at a more comprehensive set of stocks, more trading days, and a wider set of measures.

As more exchanges are planning to adopt a speed bump, a question arises: what will an additional delayed exchange add to the fragmentation of the market, and how it would affect the order flow segmentation? How will the new IEX order types and fee schedule function? Still, another difficulty in modelling the behavior of high-frequency traders remains unsolved. As O'Hara (2014) has emphasized, the trading robots may think in terms of a volume clock (e.g. several lots); alternatively, Hasbrouck and Saar (2013) argue that algos have their own machine cycle; in the meanwhile,

Table 8: Adverse Selection Measure on a Finer Time Scale (share weighted, 1–10ms)

Panel A: Large Stocks

Stock	Adverse Selection (share weighted)															
Exchange	1ms	2ms	3ms	4ms	5ms	6ms	7ms	8ms	9ms	10ms	50ms	100ms	500ms	1s	5s	10s
NYSE	0.0015	0.0021	0.0023	0.0025	0.0025	0.0026	0.0026	0.0026	0.0027	0.0027	0.0029	0.0029	0.0030	0.0031	0.0034	0.0035
NYSE Arca	0.0009	0.0011	0.0011	0.0011	0.0011	0.0012	0.0011	0.0012	0.0012	0.0012	0.0014	0.0014	0.0014	0.0015	0.0016	0.0017
NASDAQ	0.0021	0.0022	0.0022	0.0022	0.0022	0.0022	0.0023	0.0023	0.0023	0.0023	0.0026	0.0025	0.0027	0.0030	0.0032	0.0033
NASDAQ BX	0.0002	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0005	0.0005	0.0006
NASDAQ PSX	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
BYX	0.0002	0.0003	0.0003	0.0003	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0005	0.0005	0.0006	0.0007
BYZ	0.0007	0.0008	0.0009	0.0009	0.0009	0.0009	0.0009	0.0009	0.0009	0.0009	0.0010	0.0010	0.0010	0.0011	0.0011	0.0011
EDGA	0.0001	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0003	0.0003	0.0003	0.0003	0.0004	0.0004
EDGX	0.0007	0.0009	0.0009	0.0009	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0011	0.0011	0.0012	0.0013	0.0013
IEX	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0003	0.0003	0.0003

Panel B: Medium Stocks

Stock	Adverse Selection (share weighted)															
Exchange	1ms	2ms	3ms	4ms	5ms	6ms	7ms	8ms	9ms	10ms	50ms	100ms	500ms	1s	5s	10s
NYSE	0.0041	0.0052	0.0055	0.0057	0.0057	0.0057	0.0058	0.0058	0.0059	0.0060	0.0066	0.0068	0.0072	0.0073	0.0082	0.0087
NYSE Arca	0.0017	0.0019	0.0020	0.0020	0.0021	0.0021	0.0021	0.0021	0.0021	0.0021	0.0024	0.0024	0.0026	0.0027	0.0030	0.0032
NASDAQ	0.0071	0.0086	0.0087	0.0088	0.0089	0.0088	0.0089	0.0089	0.0091	0.0092	0.0096	0.0097	0.0100	0.0102	0.0111	0.0115
NASDAQ BX	0.0010	0.0015	0.0016	0.0016	0.0016	0.0017	0.0018	0.0018	0.0019	0.0019	0.0021	0.0021	0.0022	0.0023	0.0025	0.0027
NASDAQ PSX	0.0002	0.0002	0.0002	0.0002	0.0003	0.0002	0.0002	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003
BYX	0.0012	0.0016	0.0017	0.0017	0.0018	0.0019	0.0020	0.0020	0.0021	0.0022	0.0024	0.0025	0.0026	0.0027	0.0029	0.0032
BYZ	0.0016	0.0018	0.0019	0.0019	0.0020	0.0020	0.0020	0.0020	0.0020	0.0019	0.0020	0.0020	0.0021	0.0021	0.0022	0.0023
EDGA	0.0004	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0006	0.0006	0.0006	0.0006	0.0007	0.0008
EDGX	0.0013	0.0016	0.0016	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	0.0018	0.0018	0.0019	0.0021	0.0022
IEX	0.0001	0.0002	0.0001	0.0002	0.0002	0.0001	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002

(Table 8, continued)

Panel C: Small Stocks

Stock Exchange	Adverse Selection (share weighted)															
	1ms	2ms	3ms	4ms	5ms	6ms	7ms	8ms	9ms	10ms	50ms	100ms	500ms	1s	5s	10s
NYSE	0.0097	0.0114	0.0119	0.0123	0.0125	0.0125	0.0126	0.0128	0.0129	0.0129	0.0140	0.0141	0.0147	0.0152	0.0169	0.0179
NYSE Arca	0.0023	0.0027	0.0028	0.0028	0.0029	0.0029	0.0029	0.0030	0.0030	0.0030	0.0033	0.0034	0.0035	0.0036	0.0040	0.0042
NASDAQ	0.0119	0.0138	0.0141	0.0142	0.0144	0.0145	0.0146	0.0147	0.0148	0.0149	0.0161	0.0164	0.0168	0.0171	0.0185	0.0192
NASDAQ BX	0.0019	0.0024	0.0025	0.0026	0.0026	0.0026	0.0027	0.0027	0.0027	0.0027	0.0030	0.0031	0.0032	0.0033	0.0036	0.0038
NASDAQ PSX	0.0005	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0007	0.0007	0.0007	0.0007	0.0008	0.0008
BYX	0.0024	0.0029	0.0031	0.0031	0.0032	0.0033	0.0033	0.0033	0.0033	0.0034	0.0038	0.0039	0.0041	0.0042	0.0048	0.0051
BYZ	0.0025	0.0028	0.0029	0.0030	0.0030	0.0030	0.0030	0.0030	0.0031	0.0031	0.0033	0.0034	0.0035	0.0035	0.0038	0.0040
EDGA	0.0007	0.0009	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0011	0.0011	0.0012	0.0012	0.0013	0.0013	0.0015	0.0016
EDGX	0.0026	0.0030	0.0030	0.0031	0.0032	0.0032	0.0032	0.0032	0.0032	0.0032	0.0036	0.0037	0.0038	0.0039	0.0043	0.0046
IEX	0.0002	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0004	0.0004	0.0003	0.0004	0.0004	0.0004

Panel D: Dow 30 Companies

Stock Exchange	Adverse Selection (share weighted)															
	1ms	2ms	3ms	4ms	5ms	6ms	7ms	8ms	9ms	10ms	50ms	100ms	500ms	1s	5s	10s
NYSE	0.0008	0.0011	0.0012	0.0013	0.0013	0.0013	0.0013	0.0014	0.0014	0.0014	0.0015	0.0015	0.0016	0.0017	0.0019	0.0020
NYSE Arca	0.0004	0.0005	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0007	0.0007	0.0007	0.0007	0.0008	0.0008	0.0008
NASDAQ	0.0005	0.0006	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007	0.0008	0.0008	0.0008	0.0008	0.0009	0.0009	0.0010	0.0010
NASDAQ BX	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002
NASDAQ PSX	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
BYX	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0002
BYZ	0.0003	0.0004	0.0004	0.0004	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0006	0.0006	0.0006	0.0006
EDGA	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002
EDGX	0.0003	0.0004	0.0004	0.0004	0.0004	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0006	0.0006	0.0006
IEX	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001

Notes: Inverted venues, which adopt a taker-maker fee schedule during our sampling period, are marked in shade. The trades in NYSE MKT (now NYSE American), NYSE National and Chicago Stock Exchange are excluded because of no or sparse trading. The trade direction is determined by Lee and Ready (1991) (LR) approach. The time interval τ taken to evaluate these measures is 15 seconds.

Table 9: Midpoint Stability Measure on a Finer Time Scale (share weighted, 1–10ms)

Panel A: Large Stocks

Stock	Midpoint Stability (share weighted)															
Exchange	1ms	2ms	3ms	4ms	5ms	6ms	7ms	8ms	9ms	10ms	50ms	100ms	500ms	1s	5s	10s
NYSE	58.20	50.12	47.32	46.00	45.17	44.62	44.20	43.90	43.56	43.30	41.13	40.57	38.81	37.11	31.52	27.99
NYSE Arca	50.23	42.60	40.34	39.17	38.37	37.75	37.29	36.91	36.57	36.24	33.45	32.84	30.74	28.93	23.50	20.53
NASDAQ	46.15	38.82	36.97	36.00	35.35	34.94	34.66	34.36	34.10	33.84	31.81	31.40	29.74	28.25	23.73	21.03
NASDAQ BX	79.51	74.58	72.73	71.69	70.97	70.43	69.97	69.59	69.18	68.81	65.34	64.35	60.80	57.69	46.20	39.25
NASDAQ PSX	51.49	43.35	41.15	40.01	39.19	38.58	38.16	37.81	37.48	37.13	34.23	33.54	31.56	29.93	24.98	22.02
BYX	81.58	77.33	75.59	74.53	73.76	73.15	72.63	72.19	71.75	71.35	67.65	66.55	62.67	59.23	46.92	39.66
BYZ	49.92	43.10	41.05	39.97	39.36	38.92	38.60	38.26	37.94	37.63	35.22	34.72	32.83	31.13	25.82	22.61
EDGA	75.24	69.51	67.29	66.00	65.12	64.45	63.92	63.43	62.99	62.56	58.62	57.56	54.05	51.07	40.68	34.64
EDGX	48.39	40.99	38.85	37.75	37.03	36.52	36.11	35.77	35.45	35.15	32.62	32.01	30.16	28.53	23.54	20.68
IEX	82.28	79.46	78.08	77.16	76.43	75.77	75.18	74.74	74.29	73.86	69.51	68.11	63.13	59.02	45.14	37.35

Panel B: Medium Stocks

Stock	Midpoint Stability (share weighted)															
Exchange	1ms	2ms	3ms	4ms	5ms	6ms	7ms	8ms	9ms	10ms	50ms	100ms	500ms	1s	5s	10s
NYSE	47.20	42.07	39.65	38.80	38.26	37.95	37.91	37.65	37.31	37.00	34.80	34.74	33.22	31.80	26.97	24.27
NYSE Arca	49.98	45.20	43.41	42.52	41.78	41.08	40.80	40.46	40.19	39.83	36.72	35.97	33.87	32.37	27.72	25.15
NASDAQ	47.18	42.02	40.64	39.93	39.40	38.99	38.83	38.56	38.25	37.96	35.67	35.22	33.51	32.14	27.84	25.43
NASDAQ BX	70.04	65.81	64.27	63.41	62.73	62.14	61.80	61.38	60.98	60.57	57.34	56.33	53.33	50.97	42.95	38.25
NASDAQ PSX	55.68	50.31	48.40	47.30	46.56	46.11	45.62	45.26	44.90	44.52	40.91	39.84	36.88	34.86	28.78	25.08
BYX	70.19	66.41	64.88	64.04	63.31	62.73	62.30	61.90	61.48	61.12	57.80	56.68	53.70	51.32	42.74	37.87
BYZ	50.83	46.13	44.85	44.18	43.61	43.03	42.95	42.69	42.37	42.06	38.99	38.38	36.17	34.57	29.57	26.82
EDGA	63.99	59.44	57.73	56.81	56.00	55.31	54.82	54.32	53.90	53.46	49.75	48.47	45.61	43.48	36.56	32.47
EDGX	50.56	45.78	44.34	43.48	42.79	42.19	41.94	41.66	41.36	41.11	38.02	37.15	35.06	33.47	28.69	25.92
IEX	82.62	79.79	78.44	77.38	76.56	75.90	75.38	74.94	74.33	73.90	69.39	67.62	63.27	59.65	48.98	42.58

(Table 9, continued)

Panel C: Small Stocks

Stock	Midpoint Stability (share weighted)															
Exchange	1ms	2ms	3ms	4ms	5ms	6ms	7ms	8ms	9ms	10ms	50ms	100ms	500ms	1s	5s	10s
NYSE	53.09	48.40	46.47	45.74	45.20	45.21	44.93	44.44	44.14	43.83	41.27	40.96	39.66	38.61	34.36	31.97
NYSE Arca	56.28	51.98	50.56	49.88	49.07	48.74	48.37	48.07	47.81	47.46	43.43	42.59	41.11	39.97	35.45	33.10
NASDAQ	49.90	45.36	44.33	43.76	43.22	42.84	42.56	42.33	42.03	41.82	39.56	39.00	37.94	36.93	33.34	31.35
NASDAQ BX	75.31	71.73	70.61	69.91	69.32	68.90	68.41	68.08	67.81	67.52	64.59	63.77	61.71	60.24	54.15	50.54
NASDAQ PSX	55.15	50.19	48.91	48.18	47.19	46.87	46.59	46.38	46.22	46.01	43.02	42.37	40.99	39.72	34.75	32.55
BYX	75.77	72.47	71.29	70.47	69.78	69.30	68.96	68.60	68.27	67.98	64.79	63.87	61.83	60.17	53.63	49.83
BYZ	55.46	51.47	50.21	49.66	49.12	48.59	48.32	48.01	47.79	47.60	44.28	43.56	41.93	40.87	36.49	33.58
EDGA	68.88	64.75	63.14	62.38	61.41	60.69	60.31	59.96	59.66	59.38	55.42	54.56	52.78	51.36	45.72	42.08
EDGX	53.97	49.95	48.52	47.59	46.93	46.47	46.17	45.83	45.28	45.09	41.83	40.81	39.22	38.05	33.96	31.51
IEX	84.29	82.08	80.89	80.02	79.14	78.48	78.04	77.69	77.28	76.97	72.83	71.56	68.84	66.47	58.21	53.16

Panel D: Dow 30 Companies

Stock	Midpoint Stability (share weighted)															
Exchange	1ms	2ms	3ms	4ms	5ms	6ms	7ms	8ms	9ms	10ms	50ms	100ms	500ms	1s	5s	10s
NYSE	55.68	48.42	45.82	44.55	43.74	43.22	42.83	42.48	42.18	41.90	39.78	39.09	36.79	34.75	27.84	23.73
NYSE Arca	43.22	34.63	32.18	31.01	30.27	29.84	29.52	29.26	29.04	28.81	27.60	27.25	26.10	25.04	21.73	19.53
NASDAQ	50.34	44.10	41.77	40.46	39.59	39.01	38.60	38.24	37.91	37.59	35.31	34.57	32.38	30.54	24.62	21.05
NASDAQ BX	80.50	76.23	74.22	73.02	72.18	71.57	71.04	70.61	70.19	69.79	66.30	65.15	61.00	57.41	44.39	36.60
NASDAQ PSX	52.59	45.71	43.16	41.70	40.79	40.06	39.49	39.08	38.75	38.37	35.68	34.91	32.61	30.82	25.09	21.53
BYX	81.33	77.34	75.41	74.29	73.44	72.80	72.28	71.85	71.45	71.07	67.75	66.57	62.26	58.50	44.82	36.78
BYZ	50.13	43.41	41.11	39.85	39.12	38.64	38.25	37.92	37.63	37.35	35.45	34.80	32.90	31.21	25.79	22.31
EDGA	75.36	69.96	67.53	66.09	65.07	64.37	63.80	63.32	62.92	62.53	59.02	57.91	54.20	51.07	39.72	33.04
EDGX	46.73	39.47	37.08	35.85	35.06	34.56	34.18	33.86	33.58	33.30	31.47	30.91	29.21	27.72	23.04	20.14
IEX	83.43	80.45	78.91	77.93	77.10	76.38	75.83	75.41	75.02	74.65	70.48	69.01	63.52	59.14	43.79	35.30

Notes: Inverted venues, which adopt a taker-maker fee schedule during our sampling period, are marked in shade. The trades in NYSE MKT (now NYSE American), NYSE National and Chicago Stock Exchange are excluded because of no or sparse trading. The trade direction is determined by Lee and Ready (1991) (LR) approach. The time interval τ taken to evaluate these measures is 15 seconds.

Table 10: Unscaled Adverse Selection Measure on a Finer Time Scale (share weighted, 1–10ms)

Panel A: Large Stocks

Stock	Unscaled Adverse Selection (share weighted)															
Exchange	1ms	2ms	3ms	4ms	5ms	6ms	7ms	8ms	9ms	10ms	50ms	100ms	500ms	1s	5s	10s
NYSE	0.0645	0.0840	0.0916	0.0958	0.0986	0.1005	0.1020	0.1033	0.1044	0.1052	0.1132	0.1153	0.1220	0.1282	0.1433	0.1487
NYSE Arca	0.1516	0.1586	0.1605	0.1496	0.1544	0.1642	0.1535	0.1578	0.1622	0.1685	0.1990	0.2025	0.2027	0.2428	0.2513	0.2711
NASDAQ	0.3819	0.3594	0.3566	0.3474	0.3477	0.3513	0.3560	0.3596	0.3620	0.3591	0.4268	0.4131	0.4597	0.5448	0.5941	0.6116
NASDAQ BX	0.0551	0.0647	0.0626	0.0639	0.0680	0.0685	0.0696	0.0706	0.0731	0.0745	0.0849	0.0792	0.0837	0.0909	0.0965	0.1054
NASDAQ PSX	0.0165	0.0176	0.0174	0.0175	0.0193	0.0188	0.0197	0.0201	0.0187	0.0190	0.0214	0.0231	0.0218	0.0262	0.0247	0.0245
BYX	0.0422	0.0555	0.0576	0.0573	0.0583	0.0612	0.0624	0.0632	0.0625	0.0651	0.0712	0.0711	0.0765	0.0812	0.0964	0.0966
BYZ	0.0806	0.0815	0.0851	0.0850	0.0844	0.0838	0.0851	0.0839	0.0853	0.0877	0.1054	0.1030	0.0985	0.1115	0.1200	0.1226
EDGA	0.0237	0.0319	0.0342	0.0361	0.0354	0.0341	0.0351	0.0348	0.0356	0.0362	0.0404	0.0408	0.0442	0.0469	0.0511	0.0535
EDGX	0.0967	0.1078	0.1075	0.1115	0.1151	0.1163	0.1130	0.1111	0.1113	0.1103	0.1193	0.1269	0.1451	0.1582	0.1694	0.1777
IEX	0.0225	0.0248	0.0293	0.0306	0.0318	0.0349	0.0317	0.0328	0.0338	0.0336	0.0425	0.0429	0.0468	0.0551	0.0584	0.0612

Panel B: Medium Stocks

Stock	Unscaled Adverse Selection (share weighted)															
Exchange	1ms	2ms	3ms	4ms	5ms	6ms	7ms	8ms	9ms	10ms	50ms	100ms	500ms	1s	5s	10s
NYSE	0.1840	0.2243	0.2364	0.2434	0.2462	0.2489	0.2509	0.2535	0.2564	0.2592	0.2946	0.3034	0.3289	0.3449	0.4024	0.4353
NYSE Arca	0.0821	0.0980	0.1034	0.1069	0.1082	0.1095	0.1101	0.1115	0.1125	0.1136	0.1266	0.1294	0.1391	0.1480	0.1750	0.1891
NASDAQ	0.3421	0.3968	0.4068	0.4149	0.4220	0.4255	0.4279	0.4311	0.4362	0.4402	0.4769	0.4845	0.5090	0.5300	0.6092	0.6446
NASDAQ BX	0.0352	0.0453	0.0483	0.0492	0.0504	0.0512	0.0518	0.0525	0.0531	0.0537	0.0592	0.0605	0.0642	0.0664	0.0748	0.0804
NASDAQ PSX	0.0088	0.0104	0.0109	0.0114	0.0117	0.0116	0.0118	0.0118	0.0119	0.0120	0.0133	0.0136	0.0146	0.0157	0.0177	0.0182
BYX	0.0460	0.0562	0.0600	0.0617	0.0634	0.0645	0.0652	0.0659	0.0669	0.0678	0.0761	0.0777	0.0828	0.0869	0.1036	0.1133
BYZ	0.0497	0.0579	0.0603	0.0619	0.0629	0.0635	0.0641	0.0646	0.0651	0.0655	0.0721	0.0731	0.0773	0.0806	0.0904	0.0961
EDGA	0.0143	0.0174	0.0189	0.0192	0.0198	0.0204	0.0206	0.0208	0.0210	0.0214	0.0239	0.0245	0.0263	0.0276	0.0321	0.0345
EDGX	0.0486	0.0563	0.0586	0.0603	0.0615	0.0621	0.0626	0.0630	0.0635	0.0640	0.0706	0.0726	0.0773	0.0823	0.0950	0.1020
IEX	0.0060	0.0071	0.0074	0.0077	0.0081	0.0081	0.0083	0.0084	0.0084	0.0085	0.0098	0.0099	0.0105	0.0110	0.0130	0.0135

(Table 10, continued)

Panel C: Small Stocks

Stock Exchange	Unscaled Adverse Selection (share weighted)															
	1ms	2ms	3ms	4ms	5ms	6ms	7ms	8ms	9ms	10ms	50ms	100ms	500ms	1s	5s	10s
NYSE	0.3139	0.3571	0.3703	0.3886	0.3973	0.3953	0.4049	0.4105	0.4157	0.4187	0.4719	0.4735	0.5035	0.5305	0.6239	0.6723
NYSE Arca	0.0640	0.0726	0.0744	0.0753	0.0767	0.0770	0.0772	0.0783	0.0785	0.0794	0.0859	0.0882	0.0925	0.0964	0.1104	0.1183
NASDAQ	0.2456	0.2785	0.2820	0.2846	0.2897	0.2910	0.2936	0.2965	0.2995	0.3013	0.3244	0.3309	0.3462	0.3553	0.3969	0.4206
NASDAQ BX	0.0436	0.0542	0.0566	0.0576	0.0589	0.0592	0.0601	0.0603	0.0606	0.0613	0.0682	0.0701	0.0744	0.0762	0.0849	0.0902
NASDAQ PSX	0.0092	0.0106	0.0109	0.0110	0.0114	0.0115	0.0116	0.0117	0.0118	0.0119	0.0128	0.0131	0.0136	0.0137	0.0153	0.0162
BYX	0.0630	0.0736	0.0773	0.0795	0.0816	0.0825	0.0821	0.0834	0.0838	0.0844	0.0953	0.0982	0.1062	0.1089	0.1319	0.1462
BYZ	0.0454	0.0522	0.0538	0.0548	0.0558	0.0555	0.0565	0.0565	0.0568	0.0572	0.0618	0.0631	0.0660	0.0681	0.0788	0.0866
EDGA	0.0162	0.0194	0.0204	0.0210	0.0215	0.0217	0.0223	0.0224	0.0226	0.0230	0.0259	0.0269	0.0284	0.0295	0.0336	0.0355
EDGX	0.0433	0.0492	0.0505	0.0514	0.0536	0.0533	0.0534	0.0538	0.0544	0.0551	0.0615	0.0627	0.0664	0.0700	0.0794	0.0867
IEX	0.0059	0.0065	0.0075	0.0077	0.0077	0.0079	0.0079	0.0081	0.0082	0.0082	0.0092	0.0095	0.0094	0.0105	0.0115	0.0119

Panel D: Dow 30 Companies

Stock Exchange	Unscaled Midpoint Stability (share weighted)															
	1ms	2ms	3ms	4ms	5ms	6ms	7ms	8ms	9ms	10ms	50ms	100ms	500ms	1s	5s	10s
NYSE	0.0734	0.0940	0.1026	0.1074	0.1108	0.1130	0.1148	0.1163	0.1175	0.1188	0.1298	0.1336	0.1430	0.1512	0.1714	0.1786
NYSE Arca	0.0373	0.0471	0.0510	0.0532	0.0546	0.0555	0.0563	0.0569	0.0574	0.0579	0.0619	0.0631	0.0666	0.0697	0.0770	0.0797
NASDAQ	0.0432	0.0526	0.0566	0.0591	0.0608	0.0620	0.0630	0.0638	0.0645	0.0652	0.0708	0.0726	0.0775	0.0817	0.0911	0.0941
NASDAQ BX	0.0046	0.0063	0.0071	0.0076	0.0080	0.0083	0.0085	0.0087	0.0089	0.0090	0.0107	0.0112	0.0125	0.0136	0.0169	0.0182
NASDAQ PSX	0.0022	0.0028	0.0030	0.0031	0.0032	0.0033	0.0034	0.0034	0.0035	0.0035	0.0038	0.0039	0.0041	0.0043	0.0047	0.0047
BYX	0.0049	0.0067	0.0077	0.0083	0.0087	0.0090	0.0093	0.0095	0.0097	0.0099	0.0117	0.0122	0.0135	0.0146	0.0182	0.0194
BYZ	0.0270	0.0332	0.0357	0.0372	0.0381	0.0388	0.0393	0.0398	0.0402	0.0406	0.0436	0.0446	0.0471	0.0493	0.0542	0.0558
EDGA	0.0039	0.0053	0.0060	0.0065	0.0068	0.0070	0.0071	0.0073	0.0074	0.0075	0.0085	0.0088	0.0096	0.0103	0.0122	0.0129
EDGX	0.0269	0.0331	0.0358	0.0373	0.0383	0.0390	0.0396	0.0401	0.0405	0.0409	0.0445	0.0457	0.0489	0.0516	0.0582	0.0605
IEX	0.0024	0.0029	0.0031	0.0033	0.0034	0.0035	0.0036	0.0036	0.0037	0.0037	0.0042	0.0043	0.0046	0.0049	0.0056	0.0059

Notes: Inverted venues, which adopt a taker-maker fee schedule during our sampling period, are marked in shade. The trades in NYSE MKT (now NYSE American), NYSE National and Chicago Stock Exchange are excluded because of no or sparse trading. The trade direction is determined by Lee and Ready (1991) (LR) approach. The time interval τ taken to evaluate these measures is 15 seconds.

trading activities are recorded in time clock and is the exact time stamp is taken as random. As a result, researchers may have to reconcile different time concepts in evaluating special trading strategies and the exchange designs. And these issues are left to future research.

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Appendix A. Details on Data Filters and Sample Choice

Appendix A.1. Data Filters

The data filters employed In IEX's white paper (Wah et al., 2017) are different from what is customary in academic studies in empirical market microstructure, especially the comprehensive procedure suggested by Holden and Jacobsen (2014). The differences between the two treatments are summarized in Table A.11 in the Appendix, where two major issues in dealing with the DTAQ database found by Holden and Jacobsen (2014) are highlighted in Panel C and D. First, withdrawn quotes must be taken into account. Second, when only one exchange resides at *both* the NBB and NBO, related quotes are written only to the Quote File, not the NBBO File. As a result, one must merge such quotes in the Quote File with the raw NBBO file to generate an official complete NBBO File.[34]

In addition, we delete observations during 9:30–9:35 am and 3:55–4:00 pm to avoid trading sessions with abnormally large volumes around market opening and closures. To verify our argument in the modelling part, we use different selection of samples of make our results comparable with related studies. Another caveat is, some companies issued multiple tranches of stocks sharing the same ticker (SYM_ROOT) but trading at different price levels; to retain common stocks only, we delete all observations that have non-missing SYM_SUFFIX.

Appendix A.2. 120-Stock High Frequency Trading Data Set

The original tickers of 120 firms, obtained by stratified sampling, are available in Brogaard (2010, 2012), and is reproduced in Table A.12. There are many changes in the sample, as described below.

Mergers and Acquisitions. Broadcom Corporation (BRCM) was merged into Avago Technologies Ltd (AVGO), and it ceased trading after January 29, 2016. Genzyme Corp was acquired by Sanofi-aventis (later renamed as Sanofi SA; SNY), and it ceased trading after April 8, 2011.

Bare Escentuals Inc (BARE) was acquired by Japan-based Shiseido Co Ltd, and ceased trading after March 12, 2010. BRE Properties, Inc (BRE) was merged into Essex Property Trust, Inc (ESS), and ceased trading after April 1, 2014. Chattem Inc (CHTT) was acquired by Sanofi-aventis (SNY), and it ceased trading after March 10, 2010. Concur Technologies Inc (CNQR) was acquired by SAP SE (SAP) and ceased trading after December 4, 2014. CapitalSource Inc (CSE) was merged into PacWest Bancorp (PACW) and ceased trading after April 7, 2014. FirstMerit Corp (FMER) was purchased by Huntington Bancshares (HBAN), and ceasing trading after August 15, 2016. Nicor Inc (GAS) was merged with AGL Resources (AGL), and it ceased trading after December 9, 2011. Piedmont Natural Gas (NYSE: PNY) was acquired by Duke Energy (DUK), it ceased trading after October 3, 2016. Platinum Underwriters Holdings Ltd (PTP) was purchased by RenaissanceRe Holdings Ltd (RNR) and ceased trading after March 2, 2015. Rockwood Holdings Inc (ROC) was merged with Albemarle Corporation (ALB) and ceased trading after January 12, 2015. StanCorp Financial Group Inc (SFG) was acquired by Japan-based Meiji Yasuda Life Insurance Company, and ceased trading after March 7, 2016.

[34] These quotes are marked by NatBBO_Ind ='1' for stock listed in NYSE, NYSE MKT, and regional exchanges (NatBBO_Ind ='1'), or Qu_Source = "N" for and NASDAQ stocks (NatBBO_Ind ='4').

Table A.11: Data Filters

Adjustment	Wah et al. (2017)	Holden and Jacobsen (2014)
Panel A: General Filters		
Trading hours	9:30 am to 4:00 pm	9:30 am to 4:00 pm
Symbols	All tickers	Stocks that "have a primary listing on the NYSE, AMEX, or NASDAQ", which follows from Hasbrouck (2009) Exclude non-common stocks, with missing SYM_ROOT
Exchanges	Exclude NYSE National, NYSE MKT, and CHX	All
Panel B: Trade File		
Trade sale condition	Drop if Tr_SCond in 'B', 'C', 'G', 'H', 'L', 'M', 'N', 'O', 'P', 'Q', 'R', 'T', 'U', 'V', 'W', 'Z', or outside '1', 2', '3'	
Trade correction	Keep regular trades or corrected trades (Tr_Corr equals '00' or '01')	Keep regular trades (Tr_Corr equals '00') and trade price $P_t > 0$.
Zero/missing trade price	Drop bid/ask price if they are zero or missing	Drop bid/ask price or quotes if they are zero or missing; drop observations if bid price is greater than ask.
Trade-through	Drop if the trade is a trade-through (*TTE_IND* = '1')	
Valid quotes	Drop if $P_t < NBB_t$ or $P_t > NBO_t$. When computing realized spreads, keep if $B_t \quad 0.1M_t \quad P_t \quad A_t + 0.1M_t$	$S_t >$ \$5.00. Also, when the quoted spread is greater than \$5.00, and the bid price is less than the previous midpoint minus \$2.50; or the ask price is greater than the previous midpoint plus \$2.50, then the observations are dropped. Also, drop $P_t < 1$.
Panel C: Quote File		
Valid Quotes	Keep if $B_t < A_t$, $B_t < A_t$, $A_t < 1$, $A_t <= 3B_t$	Drop non-regular quotes; say, Quote_Cond NOT in 'A', 'B', 'H', 'O', 'R', 'W'; keep if $B_t < A_t$.
Canceled Quotes		Drop quotes of Quote_Cancel equals 'B'; if A_t or B_t size (price) is zero, then the price (size) is set to zero
Panel D: NBBO File		
Invalid NBBO		$NBO_t \quad NBB_t > 5$, $NBB < M_{t-1} \quad 2.5$ or $NBO_t > M_{t+1} + 2.5$; if NBB/NBO size (price) is zero, the NBB/NBO price (size) is set to zero
Incomplete NBBO		Merge with the Quote File to construct complete NBBO

Notes: The blanks in the table denote no adjustment. One ticker named BRK.A is excluded from Wah et al. (2017) for its unusual behavior. In both approaches, TRF trading are excluded.

Cbeyond Inc (CBEY) was acquired by a private company named Birch Communications Inc, and ended trading after July 18, 2014. Similarly, Knology Inc (KNOL) was merged with a subsidy of WideOpenWest Finance LLC (WOW!), and ended trading after on July 16, 2012. K-Tron International Inc (KTII) was acquired by Hillenbrand Inc (HI), and ceased trading after April 1, 2010. MAKO Surgical Corp (MAKO) was purchased by Stryker Corp (SYK), and ended trading after December 16, 2013. Maidenform Brands Inc (MFB) was acquired by Hanesbrands Inc (HBI), and ceased trading after October 4, 2013. Meadowbrook Insurance Group Inc (MIG) was acquired by the China-based Fosun Group, and ceased trading after July 7, 2015. Pre-Paid Legal Services Inc (PPD) was sold to a private firm named MidOcean Partners, and ceased trading after June 30, 2011. Retail Ventures Inc (RVI) was merged with DSW Inc (DSW), and it ceased trading after May 25, 2011.

Table A.12: 120-Stock High Frequency Trading Data Set

Group	Symbol				
Large	AA ! ARNC	AAPL	ADBE	AGN	AMAT
	AMGN	AMZN	AXP	BHI	BIIB
	BRCM ! AVGO	CB	CELG	CMCSA	COST
	CSCO	CTSH	~~DELL~~	DIS	DOW
	EBAY	ESRX	GE	GENZ ! SNY	GILD
	GLW	GOOG	GPS	HON	HPQ
	INTC	ISRG	KMB	KR	MMM
	MOS	PFE	PG	PNC	SWN
Medium	AMED	ARCC	AYI	~~BARE~~	BRE ! ESS
	BXS	CBT	CCO	CETV	CHTT ! SNY
	CKH	CNQR ! SAP	COO	CPWR	CR
	CRI	CSE ! PACW	CSL	ERIE	EWBC
	FCN	FL	FMER ! HBAN	FULT	GAS ! AGL
	ISIL	JKHY	LANC	LECO	LPNT
	LSTR	MANT	MELI	NSR	NUS
	PNY ! DUK	PTP ! RNR	ROC ! ALB	SF	SFG
Small	ABD ! ACCO	AINV	ANGO	APOG	AZZ
	BAS	BW ! MTRN	BZ	~~CBEY~~	CBZ
	CDR	CPSI	CRVL	CTRN	DCOM
	DK	EBF	FFIC	FPO	FRED
	IMGN	IPAR	~~KNOL~~	KTII ! HI	MAKO ! SYK
	MDCO	MFB ! HBI	~~MIG~~	MOD	MRTN
	MXWL	NC	NXTM	PBH	~~PPD~~
	RIGL	ROCK	ROG	RVI ! DSW	SJW

Notes: A dark shaded cell denotes a pure rename in the ticker (ABD) or a spin-off (AA); a light shaded cell marks a delisting as a result of mergers and acquisitions, or privatization (DELL). An arrow (!) shows the ticker of the new company created or the acquirer if it is listed; a delete line (~~TICKER~~) marks a complete delisting.

* Since there is considerable attrition in the 120-stock dataset, we carry out a stratified sampling similar to Brogaard, Hendershott, and Riordan (2014), but for NYSE- and NASDAQ-listed stocks separately. Specifically, we download the Membership List (June 2016 version) of Russell 3000 Index from the FTSE Russell website (*https://www.ftserussell.com*), and match the tickers with the CRSP data to compute the market capitalization for each companies. We then construct two 90-stock samples, one for NYSE-listed stocks and the other for NASDAQ-listed stocks. For each

sample, we divide the 90 stocks into three groups: large, medium, and small, where

- *Large.* 1th to 100th largest NYSE-listed (or NASDAQ-listed) stocks.
- *Medium.* 101th to 1000th largest NYSE-traded (or NASDAQ-listed) stocks that are in the Russell 3000 Membership List.
- *Medium.* 1001th to 2000th largest NYSE-traded (or NASDAQ-listed) stocks that are in the Russell 3000 Membership List,

Privatization. Dell Inc (DELL) completed a buyout and went private; it ceased trading after October 29, 2013.

Spin-off. Alcoa Inc was separated into two: the original Alcoa Inc (AA) was renamed as Arconic Inc (ARNC) and a new Alcoa Corporation (AA) is created; this change is effective from October 28, 2016.

Pure Ticker Change. In this case, the permnos of the firms do not change. ACCO Brands Corp changed its ticker from ABD to ACCO on April 30, 2012. Brush Engineered Materials (BW) changed its name to Materion Corporation (MTRN) after March 7, 2010. We then replace ABD and BW with the new tickers ACCO and MTRN, respectively.

To get the final sample tickers, we simply delete the delisted stocks, and replace old tickers with new one in the case of a pure ticker change. In the final sample, we include the following tickers:

1. *Large Firms* (36 firms). ARNC, AAPL, ADBE, AGN, AMAT, AMGN, AMZN, AXP, BHI, BIIB, CB, CELG, CMCSA, COST, CSCO, CTSH, DIS, DOW, EBAY, ESRX, GE, GILD, GLW, GOOG, GPS, HON, HPQ, INTC, ISRG, KMB, KR, MMM, MOS, PFE, PG, PNC, SWN.
   Note that BRCM, DELL, and GENZ are deleted.
2. *Medium-sized Firms* (30 firms). AMED, ARCC, AYI, BXS, CBT, CCO, CETV, CKH, COO, CPWR, CR, CRI, CSL, ERIE, EWBC, FCN, FL, FULT, ISIL, JKHY, LANC, LECO, LPNT, LSTR, MANT, MELI, NSR, NUS, SF, SFG.
   Note that BARE, BRE, CNQR, CS, FMER, GAS, PNY, DUK, PTP, ROC are deleted.
3. *Small Firms* (31 firms). ACCO, AINV, ANGO, APOG, AZZ, BAS, BZ, CBZ, CDR, CPSI, CRVL, CTRN, DCOM, KE, EBF, FFIC, FPO, FRED, IMGN, IPAR, MDCO, MOD, MRTN, MXWL, NC, NXTM, PBH, RIGL, ROCK, ROG, SJW.
   Note that BW, CBEY, KNOL, KTII, MAKO, MFB, MIG, PPD, RVI are deleted.

Appendix A.3. Dow 30 Companies

To corroborate our results that IEX does not stand out in large-cap stocks as it does in small- and medium-size stocks, we use the component companies of the Dow Jones Industrial Average Index. The tickers are shown in Table A.13; we can see that 26 out of 30 stocks are from NYSE. To ensure that all selected stocks are traded in the 10 selected exchanges, we drop the the 4 NASDAQ-listed symbols (AAPL, CSCO, INTC, and MSFT).

Table A.13: Dow 30 Companies

No.	Company Name	Symbol	Listed Exchange
1	3M	MMM	NYSE
2	American Express	AXP	NYSE
3	Boeing	BA	NYSE
4	Caterpillar	CAT	NYSE
5	Chevron	CVX	NYSE
6	Coca-Cola	KO	NYSE
7	DowDuPont	DWDP	NYSE
8	ExxonMobil	XOM	NYSE
9	General Electric	GE	NYSE
10	Goldman Sachs	GS	NYSE
11	The Home Depot	HD	NYSE
12	IBM	IBM	NYSE
13	Johnson & Johnson	JNJ	NYSE
14	JPMorgan Chase	JPM	NYSE
15	McDonald's	MCD	NYSE
16	Merck	MRK	NYSE
17	Nike	NKE	NYSE
18	Pfizer	PFE	NYSE
19	Procter & Gamble	PG	NYSE
20	Travelers	TRV	NYSE
21	UnitedHealth Group	UNH	NYSE
22	United Technologies	UTX	NYSE
23	Verizon	VZ	NYSE
24	Visa	V	NYSE
25	Walmart	WMT	NYSE
26	Walt Disney	DIS	NYSE
27	Apple	AAPL	NASDAQ
28	Cisco Systems	CSCO	NASDAQ
29	Intel	INTC	NASDAQ
30	Microsoft	MSFT	NASDAQ

Appendix B. Additional Results

Table B.14: Adverse Selection Measure on a Finer Time Scale (dollar weighted)

Panel A: Large Stocks

Stock	Adverse Selection (dollar weighted)															
Exchange	1ms	2ms	3ms	4ms	5ms	6ms	7ms	8ms	9ms	10ms	50ms	100ms	500ms	1s	5s	10s
NYSE	0.0015	0.0021	0.0023	0.0025	0.0025	0.0026	0.0026	0.0026	0.0027	0.0027	0.0029	0.0029	0.0030	0.0031	0.0034	0.0035
NYSE Arca	0.0009	0.0011	0.0011	0.0011	0.0011	0.0012	0.0011	0.0012	0.0012	0.0012	0.0014	0.0014	0.0014	0.0015	0.0016	0.0017
NASDAQ	0.0021	0.0022	0.0022	0.0022	0.0022	0.0022	0.0023	0.0023	0.0023	0.0023	0.0026	0.0025	0.0027	0.0030	0.0032	0.0033
NASDAQ BX	0.0002	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0005	0.0005	0.0006
NASDAQ PSX	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
BYX	0.0002	0.0003	0.0003	0.0003	0.0003	0.0003	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0005	0.0005	0.0006	0.0007
BYZ	0.0007	0.0008	0.0009	0.0009	0.0009	0.0009	0.0009	0.0009	0.0009	0.0009	0.0010	0.0010	0.0010	0.0011	0.0011	0.0011
EDGA	0.0001	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0003	0.0003	0.0003	0.0003	0.0004	0.0004
EDGX	0.0007	0.0009	0.0009	0.0009	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0011	0.0011	0.0012	0.0013	0.0013
IEX	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0003	0.0003	0.0003

Panel B: Medium Stocks

Stock	Adverse Selection (dollar weighted)															
Exchange	1ms	2ms	3ms	4ms	5ms	6ms	7ms	8ms	9ms	10ms	50ms	100ms	500ms	1s	5s	10s
NYSE	0.0041	0.0052	0.0055	0.0057	0.0057	0.0057	0.0058	0.0058	0.0059	0.0060	0.0066	0.0068	0.0072	0.0073	0.0082	0.0087
NYSE Arca	0.0017	0.0019	0.0020	0.0020	0.0021	0.0021	0.0021	0.0021	0.0021	0.0021	0.0024	0.0024	0.0026	0.0027	0.0030	0.0032
NASDAQ	0.0071	0.0086	0.0087	0.0088	0.0089	0.0088	0.0089	0.0089	0.0091	0.0092	0.0096	0.0097	0.0100	0.0102	0.0111	0.0115
NASDAQ BX	0.0010	0.0015	0.0016	0.0016	0.0016	0.0017	0.0018	0.0018	0.0019	0.0019	0.0021	0.0021	0.0022	0.0023	0.0025	0.0027
NASDAQ PSX	0.0002	0.0002	0.0002	0.0002	0.0003	0.0002	0.0002	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003
BYX	0.0012	0.0016	0.0017	0.0017	0.0018	0.0019	0.0020	0.0020	0.0021	0.0022	0.0024	0.0025	0.0026	0.0027	0.0029	0.0032
BYZ	0.0016	0.0018	0.0019	0.0019	0.0020	0.0020	0.0020	0.0020	0.0020	0.0019	0.0020	0.0020	0.0021	0.0021	0.0022	0.0023
EDGA	0.0004	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0006	0.0006	0.0006	0.0006	0.0007	0.0008
EDGX	0.0013	0.0016	0.0016	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	0.0018	0.0018	0.0019	0.0021	0.0022
IEX	0.0001	0.0002	0.0001	0.0002	0.0002	0.0001	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002

(Table B.14, continued)

Panel C: Small Stocks

Stock Exchange	Adverse Selection (dollar weighted)															
	1ms	2ms	3ms	4ms	5ms	6ms	7ms	8ms	9ms	10ms	50ms	100ms	500ms	1s	5s	10s
NYSE	0.0097	0.0114	0.0119	0.0123	0.0125	0.0125	0.0126	0.0128	0.0129	0.0129	0.0140	0.0141	0.0147	0.0152	0.0169	0.0179
NYSE Arca	0.0023	0.0027	0.0028	0.0028	0.0029	0.0029	0.0029	0.0030	0.0030	0.0030	0.0033	0.0034	0.0035	0.0036	0.0040	0.0042
NASDAQ	0.0119	0.0138	0.0141	0.0142	0.0144	0.0145	0.0146	0.0147	0.0148	0.0149	0.0161	0.0164	0.0168	0.0171	0.0185	0.0192
NASDAQ BX	0.0019	0.0024	0.0025	0.0026	0.0026	0.0026	0.0027	0.0027	0.0027	0.0027	0.0030	0.0031	0.0032	0.0033	0.0036	0.0038
NASDAQ PSX	0.0005	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0007	0.0007	0.0007	0.0007	0.0008	0.0008
BYX	0.0024	0.0029	0.0031	0.0031	0.0032	0.0033	0.0033	0.0033	0.0033	0.0034	0.0038	0.0039	0.0041	0.0042	0.0048	0.0051
BYZ	0.0025	0.0028	0.0029	0.0030	0.0030	0.0030	0.0030	0.0030	0.0031	0.0031	0.0033	0.0034	0.0035	0.0035	0.0038	0.0040
EDGA	0.0007	0.0009	0.0010	0.0010	0.0010	0.0010	0.0010	0.0010	0.0011	0.0011	0.0012	0.0012	0.0013	0.0013	0.0015	0.0016
EDGX	0.0026	0.0030	0.0030	0.0031	0.0032	0.0032	0.0032	0.0032	0.0032	0.0032	0.0036	0.0037	0.0038	0.0039	0.0043	0.0046
IEX	0.0002	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0004	0.0004	0.0003	0.0004	0.0004	0.0004

Panel D: Dow 30 Companies

Stock Exchange	Adverse Selection (dollar weighted)															
	1ms	2ms	3ms	4ms	5ms	6ms	7ms	8ms	9ms	10ms	50ms	100ms	500ms	1s	5s	10s
NYSE	0.0008	0.0011	0.0012	0.0013	0.0013	0.0013	0.0013	0.0014	0.0014	0.0014	0.0015	0.0015	0.0016	0.0017	0.0019	0.0020
NYSE Arca	0.0004	0.0005	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0006	0.0007	0.0007	0.0007	0.0007	0.0008	0.0008	0.0008
NASDAQ	0.0005	0.0006	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007	0.0008	0.0008	0.0008	0.0008	0.0009	0.0009	0.0010	0.0010
NASDAQ BX	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002
NASDAQ PSX	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
BYX	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002	0.0002
BYZ	0.0003	0.0004	0.0004	0.0004	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0006	0.0006	0.0006	0.0006
EDGA	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002
EDGX	0.0003	0.0004	0.0004	0.0004	0.0004	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0006	0.0006	0.0006
IEX	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001

Notes: Inverted venues, which adopt a taker-maker fee schedule during our sampling period, are marked in shade. The trades in NYSE MKT (now NYSE American), NYSE National and Chicago Stock Exchange are excluded because of no or sparse trading. The trade direction is determined by Lee and Ready (1991) (LR) approach. The time interval τ taken to evaluate these measures is 15 seconds.

Table B.15: Midpoint Stability on a Finer Time Scale (dollar weighted, 1–10ms)

Panel A: Large Stocks

Stock	Midpoint Stability (dollar weighted)															
Exchange	1ms	2ms	3ms	4ms	5ms	6ms	7ms	8ms	9ms	10ms	50ms	100ms	500ms	1s	5s	10s
NYSE	58.20	50.12	47.32	46.00	45.17	44.62	44.20	43.90	43.56	43.30	41.13	40.57	38.81	37.12	31.52	27.99
NYSE Arca	50.23	42.61	40.34	39.17	38.37	37.75	37.29	36.91	36.57	36.24	33.45	32.84	30.74	28.93	23.51	20.53
NASDAQ	46.16	38.82	36.97	36.00	35.35	34.94	34.66	34.37	34.10	33.84	31.81	31.40	29.74	28.25	23.73	21.03
NASDAQ BX	79.51	74.58	72.73	71.70	70.97	70.43	69.97	69.59	69.18	68.82	65.34	64.35	60.81	57.69	46.20	39.25
NASDAQ PSX	51.49	43.35	41.15	40.01	39.19	38.58	38.16	37.81	37.48	37.13	34.24	33.54	31.56	29.93	24.98	22.02
BYX	81.58	77.33	75.59	74.53	73.76	73.15	72.63	72.20	71.75	71.35	67.65	66.55	62.67	59.24	46.92	39.66
BYZ	49.92	43.10	41.05	39.97	39.37	38.92	38.60	38.27	37.94	37.64	35.23	34.72	32.83	31.13	25.82	22.61
EDGA	75.24	69.51	67.29	66.00	65.12	64.45	63.93	63.43	62.99	62.56	58.63	57.56	54.05	51.07	40.68	34.64
EDGX	48.39	40.99	38.85	37.76	37.03	36.52	36.11	35.77	35.45	35.15	32.62	32.01	30.16	28.53	23.54	20.68
IEX	82.28	79.46	78.08	77.16	76.43	75.77	75.18	74.74	74.29	73.86	69.51	68.11	63.13	59.02	45.14	37.35

Panel B: Medium Stocks

Stock	Midpoint Stability (dollar weighted)															
Exchange	1ms	2ms	3ms	4ms	5ms	6ms	7ms	8ms	9ms	10ms	50ms	100ms	500ms	1s	5s	10s
NYSE	47.20	42.07	39.65	38.80	38.26	37.95	37.91	37.65	37.31	37.00	34.80	34.74	33.22	31.80	26.97	24.27
NYSE Arca	49.98	45.21	43.41	42.52	41.78	41.09	40.80	40.46	40.19	39.84	36.73	35.97	33.87	32.37	27.72	25.15
NASDAQ	47.18	42.02	40.64	39.93	39.40	38.99	38.84	38.57	38.25	37.96	35.67	35.23	33.51	32.15	27.84	25.43
NASDAQ BX	70.04	65.82	64.27	63.42	62.73	62.14	61.80	61.39	60.98	60.57	57.35	56.33	53.33	50.98	42.96	38.26
NASDAQ PSX	55.68	50.31	48.40	47.30	46.56	46.11	45.63	45.27	44.90	44.52	40.91	39.85	36.88	34.86	28.79	25.08
BYX	70.19	66.41	64.88	64.04	63.32	62.74	62.31	61.91	61.49	61.12	57.80	56.68	53.70	51.32	42.75	37.88
BYZ	50.83	46.13	44.85	44.18	43.61	43.03	42.96	42.69	42.37	42.06	38.99	38.38	36.17	34.58	29.58	26.83
EDGA	63.99	59.43	57.73	56.81	56.00	55.31	54.82	54.32	53.90	53.46	49.75	48.47	45.61	43.48	36.56	32.47
EDGX	50.56	45.79	44.34	43.48	42.79	42.20	41.95	41.66	41.36	41.11	38.03	37.16	35.06	33.47	28.69	25.92
IEX	82.62	79.79	78.44	77.38	76.57	75.90	75.38	74.94	74.33	73.90	69.39	67.62	63.27	59.66	48.98	42.58

(Table B.15, continued)

Panel C: Small Stocks

Stock	Midpoint Stability (dollar weighted)															
Exchange	1ms	2ms	3ms	4ms	5ms	6ms	7ms	8ms	9ms	10ms	50ms	100ms	500ms	1s	5s	10s
NYSE	53.09	48.40	46.47	45.74	45.20	45.21	44.93	44.44	44.14	43.83	41.27	40.96	39.66	38.61	34.36	31.97
NYSE Arca	56.28	51.98	50.55	49.87	49.07	48.74	48.37	48.07	47.81	47.46	43.43	42.58	41.11	39.97	35.45	33.10
NASDAQ	49.90	45.36	44.33	43.76	43.22	42.84	42.56	42.33	42.03	41.82	39.55	38.99	37.94	36.93	33.34	31.35
NASDAQ BX	75.31	71.73	70.61	69.91	69.32	68.90	68.42	68.08	67.81	67.52	64.59	63.77	61.71	60.25	54.15	50.54
NASDAQ PSX	55.15	50.19	48.91	48.18	47.20	46.87	46.59	46.38	46.22	46.01	43.02	42.37	40.99	39.72	34.75	32.55
BYX	75.77	72.47	71.29	70.47	69.78	69.30	68.96	68.60	68.27	67.98	64.79	63.87	61.83	60.17	53.63	49.82
BYZ	55.46	51.47	50.21	49.66	49.11	48.59	48.32	48.00	47.79	47.60	44.28	43.56	41.93	40.87	36.49	33.58
EDGA	68.88	64.76	63.14	62.38	61.42	60.69	60.31	59.96	59.66	59.39	55.42	54.56	52.78	51.36	45.72	42.08
EDGX	53.97	49.95	48.52	47.59	46.92	46.47	46.17	45.83	45.28	45.09	41.83	40.81	39.22	38.05	33.96	31.50
IEX	84.29	82.08	80.89	80.02	79.14	78.47	78.03	77.69	77.28	76.97	72.83	71.55	68.83	66.47	58.21	53.16

Panel D: Dow 30 Companies

Stock	Midpoint Stability (dollar weighted)															
Exchange	1ms	2ms	3ms	4ms	5ms	6ms	7ms	8ms	9ms	10ms	50ms	100ms	500ms	1s	5s	10s
NYSE	55.68	48.42	45.82	44.55	43.74	43.22	42.83	42.48	42.19	41.90	39.78	39.09	36.79	34.75	27.84	23.73
NYSE Arca	43.22	34.63	32.18	31.01	30.27	29.84	29.52	29.26	29.04	28.81	27.60	27.25	26.10	25.04	21.73	19.53
NASDAQ	50.34	44.10	41.77	40.46	39.59	39.01	38.60	38.24	37.91	37.59	35.31	34.57	32.38	30.54	24.62	21.05
NASDAQ BX	80.50	76.24	74.22	73.02	72.18	71.57	71.05	70.61	70.20	69.79	66.30	65.15	61.00	57.41	44.39	36.60
NASDAQ PSX	52.59	45.71	43.16	41.70	40.79	40.06	39.49	39.08	38.75	38.38	35.68	34.91	32.61	30.82	25.10	21.53
BYX	81.33	77.34	75.41	74.30	73.44	72.80	72.28	71.85	71.46	71.07	67.75	66.57	62.26	58.50	44.82	36.78
BYZ	50.13	43.42	41.11	39.85	39.12	38.64	38.25	37.92	37.63	37.35	35.45	34.80	32.91	31.21	25.79	22.31
EDGA	75.36	69.96	67.53	66.09	65.07	64.37	63.81	63.32	62.92	62.53	59.02	57.91	54.20	51.07	39.72	33.04
EDGX	46.73	39.47	37.08	35.85	35.06	34.56	34.18	33.86	33.58	33.30	31.47	30.91	29.21	27.72	23.04	20.14
IEX	83.43	80.45	78.91	77.93	77.10	76.38	75.83	75.41	75.02	74.65	70.48	69.01	63.52	59.14	43.80	35.30

Notes: Inverted venues, which adopt a taker-maker fee schedule during our sampling period, are marked in shade. The trades in NYSE MKT (now NYSE American), NYSE National and Chicago Stock Exchange are excluded because of no or sparse trading. The trade direction is determined by Lee and Ready (1991) (LR) approach. The time interval τ taken to evaluate these measures is 15 seconds.