Intentional Access Delays, Market Quality, and Price Discovery: Evidence from IEX Becoming an Exchange*

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Abstract

This paper exploits cross-sectional variation in trading activity and the staggered securities phase-in when the Investors Exchange (IEX) becomes a national securities exchange to study the effects of intentional access delays on market quality and price discovery. Market quality improves after IEX becomes an exchange for securities with high historical IEX market share. Price discovery improves overall, although IEX's contribution to price discovery remains small. Intermarket Sweep Order activity decreases overall, coinciding with improvements in price discovery. In a second natural experiment where IEX's ECN goes dark in 28 symbols there is no change in market quality or price discovery. The findings in this paper suggest that protected markets with symmetric speed bumps may be a feasible solution to deemphasize speed in lieu of regulatory intervention.

JEL Classification: G14, G18
Keywords: IEX, speed bump, Rule 611, Reg NMS, dark pool

In June of 2016 the U.S. Securities and Exchange Commission (SEC) issued a new interpretation of Rule 611, the "Order Protection Rule," to allow for *de minimis* intentional access delays to automated exchange quotations.[1] This decision paved the way for the SEC's approval of the controversial Investors Exchange (IEX) application to become a national securities exchange.[2] One of the key questions surrounding IEX's application was whether it should qualify for a "protected quote" under Rule 611's "immediate access" requirement because of its 350-microsecond *speed bump* on all incoming orders and outgoing messages. The debate over the potential effects of IEX's speed bump generated widespread interest from market participants, academics, and regulators.[3] Ultimately, the SEC found that the speed bump was consistent with the new interpretation of Rule 611 and the goals of Regulation National Market System (Reg NMS).[4]

In this paper, I exploit cross-sectional variation in trading activity and the staggered securities phase-in on IEX from August–September of 2016 to provide causal evidence on the effects of intentional access delays on market quality and price discovery. The identification is aided by three institutional details. First, the staggered phase-in is based on the first letter of each trading symbol and all NMS symbols trade on IEX (ATS and exchange)–which mitigates potential selection biases. Second, both before and after becoming an exchange, IEX does not charge for data, or to post or take displayed liquidity, which mitigates concerns of increased market complexity costs associated with new venues (e.g., due to fragmentation or access fees).[5] Finally, when IEX becomes an exchange it receives a "protected quote," meaning that participants can no longer ignore its quotes–and by extension its speed bump–as they could when IEX was an ATS. Because of trade-through restrictions, if

[1] `https://www.sec.gov/rules/interp/2016/34-78102.pdf`

[2] `https://www.sec.gov/rules/other/2016/34-78101.pdf`

[3] The SEC received 474 comment letters both for and against IEX's application. In contrast, BATS and EDGX's exchange applications only received four total comment letters.

[4] See Commission Interpretation Regarding Automated Quotations Under Regulation NMS, and Order of the Commission In the Matter of the Application of Investors' Exchange, LLC for Registration as a National Securities Exchange.

[5] The IEX exchange is not a "new venue" per se, as it does not offer any additional services compared to its ATS. See Section 1 for a more detailed description of the IEX market structure.

IEX has the best quote, no venue is allowed to execute trades at inferior prices. Instead, such orders must be cancelled, posted to the book, or routed to IEX.[6]

I find that when IEX becomes an exchange and receives a protected quote, symbols where interactions with IEX's speed bump are ex-ante most likely–e.g., symbols with the highest average daily market share by trading activity over Q2 of 2016–experience a net improvement in market quality as measured by quoted, effective, and realized spreads. The efficiency of price discovery improves overall as measured by absolute return autocorrelations, variance ratios, and the speed at which information about the market is compounded into individual security returns.

The reduction in trading costs (spreads) is broadly consistent with recent theories on how speed advantages may be used to exploit mechanical arbitrage opportunities. These theories suggest that market makers face adverse selection from fast traders even in the absence of traditional "fundamental" informed trading. For instance, Budish et al. (2015) defines "quote sniping" as the mechanical arbitrage of taking "stale" quotes before market makers can cancel. In his Comment Letter on IEX's Exchange Application, Eric Budish argues that IEX's speed bump may be able to mitigate quote sniping as it allows IEX's pegged orders to avoid executing against market orders at stale prices.[7] Moreover, cross-sectional differences in spreads in response to IEX's protected quote are consistent with recent theory suggesting that exchange speed is a double-edged sword for market makers (Menkveld and Zoican, 2016). On one hand, faster exchanges allow market makers to update their quotes faster, reducing spreads. On the other hand, higher exchange speed results in a higher probability of quote sniping. Hence, the results support this more nuanced view of the net effects of speed on trading costs.

[6]Even if IEX does not have the best quote, a market participant with no intention of trading on IEX may be required to check IEX's quotes to comply with the trade-through restriction. For example a market participant wishing to buy a large quantity on NYSE at 10.02 when NASDAQ is at 10.00 (NBO) and IEX is at 10.01 would be required to submit an order for the full displayed size at IEX and NASDAQ before trading-through at NYSE. See also, Division of Trading and Markets Memo on Rule 611 of Regulation NMS to the Equity Market Structure Advisory Committee.

[7]Specifically, Budish et al. (2015) and Baldauf and Mollner (2015) argue that access delays would allow market makers to cancel or modify their limit orders to mitigate quote sniping. Budish et al. (2015) argues that IEX's speed bump combined with its pegged orders essentially functions as such an access delay.

The overall improvement in price discovery is harder to reconcile. In his Comment Letter, Eric Budish argues that a weakness of IEX's market structure is that it only prevents latency arbitrage for (non-displayed) pegged orders, and does not help displayed limit orders which contribute to price discovery. As such, IEX's market design can only succeed so long as it is able to "free-ride" off of other exchanges' price discovery. Indeed, when I decompose exchanges' contributions to price discovery using a state-space model, I find that IEX's information share does not increase as it transitions from an ATS to an exchange. Hence, the improvements in price discovery are not directly attributable to IEX. Instead, it may be that the speed bump affects other forms of mechanical or regulatory arbitrage beyond "quote sniping," which impacts price discovery.

To shed light on a potential price discovery mechanism, I examine the effect of the speed bump on Intermarket Sweep Orders (ISOs). ISOs make up nearly half of all trades and trading volume and may affect the formation of prices in two ways. One the one hand, ISOs appear to be an important part of informed institutional trading strategies–which suggests that ISOs contribute to price discovery (Chakravarty et al., 2012). On the other hand, ISOs may be used to conduct order anticipation, which crowds out fundamental informed traders and slows price discovery (e.g., Yang and Zhu (2016) and Baldauf and Mollner (2015)).[8]

After IEX receives a protected quote, I find an overall reduction in ISO activity as measured by ISO to trade volume, ISO to submitted order volume, and the number of ISO executions to the number of order cancellations. The market-wide decrease in ISOs corresponds to market-wide improvements in price discovery. As with the market quality results, I interpret these findings as suggesting that the speed bump reduces speed-related mechanical arbitrage opportunities. Moreover, this finding is consistent with Weller (2015), which shows that proxies for algorithmic trading are related to lower price efficiency.

One potential externality of IEX's speed bump is that it favors dark over lit liquidity. In a Comment Letter to the Commission regarding IEX's Exchange Application, Charles Jones raises the issue that IEX may hurt pre-trade transparency because a speed bump could give better executions to

[8]In a Comment Letter responding to the SEC's Market Structure Concept Release, high-frequency trading firm Tradeworx describes a regulatory arbitrage strategy using ISOs to conduct "order-anticipation." I discuss the ISO–order-anticipation–price discovery channel in more detail in Section 6.

dark liquidity over displayed liquidity as dark orders are re-priced without a delay.[9] Unfortunately, this question cannot be addressed using the IEX exchange phase-in since order protection does not apply to dark liquidity.

To examine the issue of IEX's potential prioritization of dark liquidity, I rely on a second experiment where IEX's ATS goes dark and estimate the effect on volume, market quality, and price discovery following Hendershott and Jones (2005) (the "Island study"). Hendershott and Jones show that when the Island ATS goes dark and stops displaying quotes in three active ETFs market share drops, spreads increase, and price discovery worsens. Like Island, IEX goes dark to comply with Regulation ATS' display requirement for venues above a five percent average daily trading volume threshold. However, unlike Island, IEX chooses to comply by no longer accepting displayed orders–prioritizing dark liquidity over all displayed liquidity.

Expanding on the Island study, I estimate the treatment effect of IEX going dark on 28 symbols between 2015–2016, with a counterfactual sample of 66 symbols that are just under the Reg ATS threshold and never go dark. In contrast to the Island study, I find that when IEX goes dark, there is no change in IEX market share, overall market quality, or price discovery. These results suggest that the prioritization of dark liquidity on IEX is not harmful–at least given recent market shares.

This paper contributes to the continuing debate on market structure design and regulation by showing that symmetric speed bumps may be beneficial for market quality (see SEC 2010 Concept Release on Equity Market Structure).[10] Former Securities and Exchange Commission Chair Mary Jo White has argued in favor of "competitive solutions that could be adopted by trading venues."[11] The new interpretation of Rule 611 marks a significant step towards deemphasizing speed by allowing exchanges to compete in providing heterogeneous speed offerings.[12] The evidence in this paper shows

[9] Comerton-Forde and Putniņš (2015) shows that high levels of dark trading appear to harm price discovery–low levels may have no effect or may be beneficial.

[10] Among the proposed solutions to reduce speed advantages are bans on high-frequency trading, taxes on trading or technology investment, affirmative or negative obligations for certain market participants, and a broad class of "speed limits" (see Harris (2013)).

[11] See Chair Mary Jo White's speech "Enhancing Our Equity Market Structure" `https://www.sec.gov/news/speech/2014-spch060514mjw`.

[12] NYSE American re-launched with the addition of a 350-millisecond speed bump in direct competition with IEX `http://bloomberg.com/news/articles/2017-07-24/nyse-american-opens-as-retort-to-exchange-rabble-rouser-iex`.

that (symmetric) speed bumps may be broadly beneficial, which suggests that competitive solutions to deemphasize speed may be feasible.

The remainder of this paper is organized as follows. Section 1 begins with a brief literature review, and then provides institutional details related to IEX's operations, Rule 611, and a selective review of the Comment Letters and common concerns related to IEX's exchange application. Section 1 concludes with testable hypotheses. Section 2 discusses data sources, describes the staggered phase-in and the identification strategy, and presents variable definitions and summary statistics. Section 3 presents results on market quality, and Section 4 on price discovery. Section 5 describes the framework used to decompose venues' contributions to price discovery. Section 6 examines the effect of access delays on ISOs. Section 7 studies the effect of IEX going dark on market share, market quality, and price discovery. Section 8 contains robustness tests. Section 9 concludes and provides a discussion of policy recommendations.

1 Background and Hypotheses

1.1 Related Literature

This paper contributes to the burgeoning academic literature on "high-frequency market microstructure" (viz. O'Hara (2015)) in two ways. First, the findings in this paper provide empirical evidence supporting recent theoretical papers focused on the effects of speed on market quality and price discovery (e.g., Menkveld and Zoican (2016), and Yang and Zhu (2016) respectively). Second, this paper adds to the recent empirical literature examining speed and market quality. Shkilko and Sokolov (2016) shows that spreads decrease when weather interferes with microwave networks relied upon by high-frequency traders. Chakrabarty et al. (2016) shows that spreads and price efficiency decline when the SEC bans naked access to exchanges, which increases costs for some high-frequency trading firms. Chen et al. (2016) shows that spreads and order cancellations increase when the Canadian exchange TSX Alpha adds an asymmetric speed bump, inverts its fee structure to charge for bypassing the speed bump, and loses its protected quote. In contrast to these papers, the intentional access delay studied in this paper affects all participants equally. In addition, as discussed in detail later in this section, the

IEX Phase-in is free of other confounding market structure changes such as access fees.

Finally, this paper complements the recent theoretical literature on market design and regulation. For instance, Biais et al. (2015) compares the gains from trade with slow markets versus a tax on high-frequency traders' technology investments. Budish et al. (2015) argues that the SEC should overhaul Reg NMS and replace continuous trading with discrete time frequent batch auctions. Baldauf and Mollner (2015) considers asymmetric access delays similar to a proposal by CHX. Pagnotta and Philippon (2016) argues that Rule 611 results in an equilibrium of fragmented markets characterized by high speed but low allocative efficiency. Eric Budish's 2017 AEA/AFA Address "Will the Market Fix the Market?" (Budish et al., 2017) echoes the broader question raised by former Chair White–can market participants innovate to deemphasize speed in financial markets, or do regulators need to develop new rules and regulations? The findings in this paper suggest that IEX's speed bump, and subsequent fair access delay proposals, may be a feasible market solution in lieu of regulatory intervention.

1.2 Institutional Details

This section briefly summarizes and discuss IEX's unique market structure from an institutional, regulatory, and academic perspective. A full description of IEX's operations is available in Exhibit E of IEX's Form 1 Filing. For more on the regulatory considerations see SEC Order approving the IEX Exchange and the Final Commission Interpretation. Comment Letters, many from practitioners, are also available online.

IEX Operations

IEX began operations as a dark pool Alternative Trading System (ATS) in October of 2013.[13] On April of 2015 IEX began operating a lit Electronic Communications Network (ECN)–allowing displayed orders and disseminating displayed trades and top-of-book quotes (the TOPS system).[14] On June 17th, 2016 the SEC approved IEX's application, making it the first venue of its kind to become a national securities exchange.[15]

[13] `https://www.iextrading.com/trading/alerts/2013/001/`

[14] `https://www.iextrading.com/trading/alerts/2015/005/`

[15] See supra note 1.

IEX is best known for its 350-microsecond "speed bump"–implemented with a "shoebox" of coiled fiber–which slows down all incoming and outgoing messages to and from market participants.[16] This includes marketable orders seeking resting liquidity, limit orders, order cancellations, as well as trade execution and quote messages published to their direct feed, but not the SIP. IEX claims that the speed bump is inconsequential for "regular" (i.e., non high-frequency) traders, but that the 350 microseconds is enough to mitigate speed advantages that high-frequency traders typically enjoy. For example, traders in New Jersey are able to gather data from the various exchange data centers within 250 microseconds, factoring in minimum geographic latencies. IEX argues that their speed bump allows the exchange enough time to reprice orders before high-frequency traders can pick off potentially stale quotes.[17]

IEX is also known for its pegged order types, which make up the majority of their executed volume. Pegged orders on IEX depend on the speed bump to execute–without any access delay to the order book–against *current* market prices. As mentioned above, the speed bump delays all incoming trade messages; however, the IEX matching engine takes in direct feed data from other exchanges without traversing the coil. This allows the matching engine time to compute the prevailing NBBO so that pegged orders do not execute at incorrect or "stale" prices. For example, the Discretionary Peg or DPEG, is a non-displayed midpoint pegged order designed to track the NBBO midpoint, while avoiding execution during "crumbling quote" periods when the NBBO is about to change. This is accomplished via a logit which predicts changes in the NBBO by tracking changes in depths.[18]

IEX earns revenue from matching non-displayed orders, and does not charge for matching displayed orders. As of the exchange application, it does not conduct listings; charge membership, direct connectivity fees; pay rebates; nor does it offer co-location services. By becoming an exchange, it earns additional revenue from the SIP Revenue Pool with other UTP Plan Members.[19]

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[16] Similar coils are used at exchange co-location facilities to ensure customers have equal access to exchange servers despite differences in the placement of customers' boxes within the same facility.

[17] See IEX CEO Brad Katsuyama's panel discussion at the George Mason Law and Economics Center, and the FIA PTG Letter comment letter.

[18] The SEC approved IEX's application to extend crumbling quote protection to its Primary Peg Orders in March of 2017.

[19] `http://www.reuters.com/article/iexgroup-exchange-idUSL1N11M1C420150916`

Rule 611: "Immediate Access" and Order Protection

The SEC approval of IEX's application to be a national exchange required a new interpretation of Rule 611 of Regulation NMS to allow for *de minimis* intentional access delays. Rule 611 protects the best automated quotes of exchanges by obligating other venues to not execute trades at inferior prices. In practice, if a venue has inferior quotes, then it may cancel, post, or route the order to another venue with better priced quotes. Because Rule 611 prevents "trading-through" the best quotes it is often called the "Order Protection Rule."

Rule 611 was written to ensure market participants have "immediate," fair, and efficient access to exchange quotes in automated markets.[20] When the rule was written in 2005 one of the main concerns was to avoid access delays–measured in seconds–in manual markets. The original interpretation of Rule 611 specifically precludes any venue with an intentional access delay from qualifying for a protected quote.

Although the Commission Interpretation does not specify a *de minimis* threshhold, it maintains that intentional access delays of less than one millisecond "may be at a *de minimis* level [...] consistent with the goals of Rule 611 [...] because such delays are within the geographic and technological latencies experienced by market participants today." Moreover, the Interpretation does not provide blanket approval for all *de minimis* access delays. New access delays must be "fairly applied" and are "subject to notice, comment, and the Commission's separate evaluation" consistent with the Exchange Act.

Comment Letters and Common Concerns

One of the most frequently cited concerns about IEX is the fact that the majority of trades on IEX occur in the "dark."[21] Critics of dark pools point to their lack of pre-trade transparency as a potential threat to market quality and price discovery.[22] However, Comerton-Forde and Putniņš (2015) shows that only high levels of dark trading appear to harm price discovery–low levels may have no effect or may be beneficial. IEX's average daily market

[20] `https://www.sec.gov/spotlight/emsac/memo-rule-611-regulation-nms.pdf`

[21] See footnotes 212–214 of the Commission Order.

[22] Recent theory suggests that introducing a dark pool may result in informed trading concentrating in lit exchanges, resulting in lower exchange liquidity (Zhu, 2014).

share never exceeds 21% for any symbol in Q2 of 2016. Therefore, even if IEX attracts additional dark liquidity as an exchange, it should not affect market quality barring a significant increase in market-wide dark trading.

A related concern is that IEX's speed bump favors dark over lit liquidity. Specifically, in a Comment Letter Charles Jones considers a hypothetical exchange where lit orders face a speed bump, and dark orders may be re-priced without a delay. Jones argues that such an exchange model indirectly subsidizes dark trading, and may harm pre-trade transparency. However, because there is no change in how dark orders are ranked, priced, or executed when IEX becomes an exchange, there is no reason to expect any effect around the exchange phase-in. I address the issue of prioritizing dark liquidity in a different setting in Section 7.

Another concern is that new exchanges bring additional connectivity requirements, which may create negative externalities resulting from increased market complexity (e.g., due to fragmentation or access fees). There are many channels through which increased market complexity may affect market quality. For example, Easley et al. (2016) finds that the practice of selling exchange data harms market quality as differential access makes public information private for some investors. Malinova and Park (2015) finds that spreads decrease following a change in trading fees on the Toronto Stock Exchange. O'Hara and Ye (2011) shows that market fragmentation improves market quality. However, when IEX launches its ECN in 2015–going from a pure dark pool to allowing displayed orders–it makes its feed of real-time trades and quotes free to the public, and makes posting and taking liquidity for displayed orders free as well.[23] When IEX becomes an exchange it maintains free access to data and displayed liquidity, which mitigates concerns of access fees on market quality.[24] Furthermore, IEX does not change any of its services during the exchange phase-in (e.g., adding order types), hence there is no reason to expect meaningful increases in market fragmentation.[25]

[23] See https://www.iextrading.com/trading/alerts/2014/023/, and https://www.iextrading.com/trading/alerts/2015/005/.

[24] https://www.iextrading.com/trading/alerts/2016/036/.

[25] IEX consolidates the number of routing options from five to two, but tests all of these changes in July, ahead of the Exchange Phase-in Period (see Router Redesign Test Phase Begins). IEX also re-designs its router to add a speed bump between its Router and Order Book Systems (see Router Redesign). Routed volume makes up about one-third of average IEX volume.

In conclusion, the only relevant change for market participants is the addition of the protected quote for IEX's best quotes. I discuss the potential economic effects of the protected quote in the next section.

1.3 Hypotheses

Granting IEX a protected quote means that its best quotes are disseminated to the SIP, and allows it to contribute to the calculation of the National Best Bid or Offer (NBBO). It also brings its speed bump online in the National Market System.[26] Even if a market participant has no intention of trading at IEX, and IEX is not at the NBBO, the participant may still be obligated to check IEX's quotes–facing the access delay–to comply with the trade-through restriction. In short, once IEX becomes an exchange, the access delay to its quotes can no longer be ignored. In this section, I discuss three hypotheses on how IEX's intentional access delay may affect market conditions.

H0 No Change: The Commission Interpretation states that "delays of less than a millisecond [...] may be at a *de minimis* level [...] because such delays are within the geographic and technological latencies experienced by market participants today." For example, a trader in New York sending an order to the CHX exchange in Chicago would experience delays of well over 350 microseconds. Virtu Financial, a high-frequency trading firm, argues that the IEX speed bump has had "no impact" on its market making abilities. If the IEX access delay is *de minimis*, then we expect no change in market quality or price discovery.

H1A Market Quality Deteriorates: The IEX speed bump may be thought of as a "Tobin" or transaction tax on high-frequency trading activity. Biais et al. (2015) argues that a per-trade tax would discourage HFT. If the speed bump discourages low-latency liquidity provision and price discovery, then securities with high IEX market share may experience decreased market quality and decreased price discovery.[27]

H1B Market Quality Improves: In his Comment Letter to the Commission, Eric Budish argues that IEX's speed bump deters quote sniping of pegged (non-displayed or dark) orders. However, Budish cautions that IEX's

[26] In a Comment Letter the NYSE argues that the IEX speed bump is like requiring certain cars on the Autobahn to slow down or turn off their lights–creating a "calamity" for the entire system.

[27] The speed bump could further harm price discovery if it forces investors to trade against stale quotes as prices adjust to reflect fundamentals.

speed bump does not benefit displayed orders, and therefore does not improve price discovery. If IEX slows down markets–reducing adverse selection from high-frequency traders–then securities with high IEX market share may experience increased market quality, with no change in price discovery.

The hypotheses and predictions are summarized in Table 1 below.

Table 1 here

2 Data and Empirical Methodology

2.1 Data Sources

The data comes from three sources. The primary source of trades and quotes is the NYSE TAQ database covering August and September of 2016. The sample period ends in September before the roll-out of the Tick Size Pilot in October of 2016 which mechanically impacts spreads in a manner unrelated to this study. IEX trades and top-of-book quotes are provided by the IEX Group and correspond to the publicly available TOPS feed. Securities characteristics–including proxies for algorithmic trading–come from the SEC's MIDAS Market Structure Metrics website.

I use all valid trades and quotes from TAQ following Holden and Jacobsen (2014) and merge the trades with the prevailing (complete) NBBO quotes.

2.2 Identifying the Effect of Intentional Access Delays

The staggered IEX exchange symbol phase-in provides a natural experiment setting to evaluate the effect of intentional access delays using a differences-in-differences framework. Figure 1 provides a timeline of the symbol phase-in process.

Figure 1 here

The "treatment" takes place when the intentional access delay comes online for a particular symbol (e.g., VG) starting when IEX begins trading the symbol as an exchange (August, 19th 2016 in this case). For exposition purposes, I define the "treatment group" as the set of symbols where interactions with IEX's speed bump are ex-ante most likely–e.g., symbols in the top tericle of average daily trading activity on IEX over Q2 of 2016 when it was still an ATS. Similarly, I define the "control group" as the symbols in the bottom tercile of trading activity on the IEX ATS. Treatment group symbols are most likely to be impacted by the access delay to their respective quotes, whereas control group symbols are essentially unaffected by the access delay. As an alternative definition of treatment and control groups, in Section 8, I partition symbols based on the amount of time IEX's quotes are at or inside the NBBO.[28] Symbols with competitive quotes on IEX are most likely to be impacted, whereas symbols without competitive quotes on IEX should rarely experience an access delay.

This differences-in-differences design has several advantages that facilitate the identification of the treatment effect. First, all NMS symbols trade on IEX, hence there is no "selection bias" as the sample covers the entire market. Second, the timing of the treatment is exogenous with respect to stock characteristics (e.g., IEX trading activity) as it is applied based on ticker symbol. Third, IEX market activity is easily observable prior to the treatment, which means that the assignment into treatment and control groups should not be affected by unobservable factors.[29] The key disadvantage of this empirical design is that, by the end of the sample, all control are eventually "treated." However, this likely biases the estimated differences between treatment and control groups towards zero, and hence attenuates the estimate of the treatment effects.

In order to estimate average treatment effects I run regressions of the form:

$$\begin{aligned} y_{i,t} =& \beta_0 + \beta_1 ProtectedQuote + \beta_2 Z_i \\ &+ \beta_3 ProtectedQuote \times Z_i + \beta_4 X_{i,t} + \varepsilon_{i,t}, \end{aligned} \tag{1}$$

where $y_{i,t}$ is a measure of market quality or price discovery, discussed in more detail below, $ProtectedQuote$ is a (0,1) indicator for when a security begins trading on the IEX exchange, Z_i is coded (-1,0,1) representing securities in low, mid, and high terciles of average daily IEX market share (time at/inside the NBBO) over Q2 of 2016 based on the number of trades executed (IEX

[28] A venue is "inside" the NBBO if its best bid is greater than or equal to the NBB or if its best offer is less than or equal to the NBO. Once IEX becomes an exchange, its quotes contribute to the NBBO, hence it can only be "at" the NBBO.

[29] Formally, the conditional independence assumption is satisfied. Note that identification does not require the stronger i.i.d. assumption obtained in a randomized controlled trial.

quote updates).[30] *ProtectedQuote* captures the overall average treatment effect. Z_i captures differences between the treatment group and the control group. $ProtectedQuote \times Z_i$ is an interaction term which captures the difference in the treatment effect between treatment and control symbols (the average treatment effect on the treated). $X_{i,t}$ is a vector of control variables.

2.3 Main Variable Definitions

The three measures of market quality are the duration-weighted average dollar quoted spreads, and the volume-weighted average dollar effective spreads and realized spreads. All spreads are constructed using NBBO quotes. For effective spreads I match trades to one-millisecond prevailing NBBOs, and for realized spreads I use the midquote in force five minutes after the trade.[31]

The three price discovery measures are absolute return autocorrelations (e.g., Hendershott and Jones (2005)), variance ratios (Lo and MacKinlay, 1988), and an intraday adaptation of the Hou and Moskowitz (2005) price delay measure.[32] All price discovery measures are constructed using NBBO midquote returns. I also decompose the contributions to price discovery using a state-space model from De Jong and Schotman (2010) analogous to the information shares from Hasbrouck (1995). I describe the state-space model in detail in Section 5.

To mitigate idiosyncratic measurement errors, I also construct a market quality factor (and a price discovery factor) as the first principal component of the three market quality (price discovery) measures.[33] Each factor variable is scored on a scale from zero to one where larger values indicate higher illiquidity (less efficient price discovery).

[30] This coding estimates the difference in the treatment effect between top tercile (treatment) and bottom tercile (control) symbols, but achieves greater statistical efficiency (see Gelman and Park (2009)). Efficiency is valuable given the small amount of exogenous time-series variation in the data—i.e. a single event.

[31] Bessembinder (2003) discusses these measures of trade execution costs. Effective spreads are a better measure of trading costs for trades that occur away from the quotes. Realized spreads measure the adverse selection costs of trading based on the market's assessment of the private information conveyed in trade executions.

[32] See the 10 for more detailed definitions of each measure which come from Comerton-Forde and Putniņš (2015).

[33] I also include the three equal-weighted spreads in the computation of the market quality factor.

The control variables are daily securities characteristics from the SEC MIDAS Market Structure Metrics website averaged over Q2 of 2016. I use three proxy variables for algorithmic trading: the cancel-to-trade ratio, the trade-to-order ratio, and the ratio of odd-lots to trades following Weller (2015). I also include the decile rank of the security in terms of market capitalization, volatility, and turnover.

2.4 Summary Statistics

Table 2 presents summary statistics. Panel A summarizes the main variables of interest for the period August 1st–August 18th just before the IEX exchange Phase-in. The median stock in the sample has an average Quoted Spread of 12 cents, Effective Spread of 8 cents, and Realized Spread of 5 cents. Consistent with the low spreads, the median stock has a small Illiquidity score of 0.08. The median stock in the sample scores low on return Autocorrelations, but high on Variance Ratios, Price Delays, and high on overall Price Discovery (In)efficiency, consistent with the existence of market frictions in the price discovery process (i.e. markets are less than perfectly efficient). The median stock has an average IEX market share of 1.2%.[34] Bottom tercile symbols trade less than 0.5% of the time on IEX, whereas top tercile symbols trade on IEX more than 1.7% of the time. Despite IEX's relatively low market share and lack of a protected quote, its quotes are inside the NBBO on average nearly 20% of the time, with significant heterogeneity across symbols. Bottom tercile symbols are essentially never inside the NBBO, whereas top tercile symbols have quotes inside the NBBO nearly 30% of the time. The median symbol has quotes inside the NBBO 8% of the time.

Panel B presents a more detailed view of IEX activity over Q2 of 2016. IEX's trading volume is heterogeneous–ranging from odd-lots to large blocks–with a typical trade size of a round lot. The median symbol-day on IEX involves 436 trades, of 73,753 shares, worth one million dollars. The average trade size (value) for the median stock is 152 ($2,806). The median symbol among those with at least one block trade has six block trades, for a total of 59,542 shares, worth one million dollars.[35] The median symbol among those with at least one odd lot trade has 78 odd lot trades, for a total of 1,905

[34]IEX reports market share based on volume executed, whereas I focus on market share in terms of the number of trades executed.

[35]A block is defined as a trade of at least 10,000 shares or $200,000.

shares, worth 28 thousand dollars. IEX's quotes are inside the NBB (NBO) 0.67% (0.77%) of the time, and inside one or more sides of the NBBO 1.47% of the time for the median symbol.

Table 2 here

2.5 IEX Market Share and Time at the NBBO

Figure 2 plots IEX market share (% of Trades, Volume, and dollar Volume) from January of 2014 to September of 2016. IEX market share (% of Volume) gradually increases from 0.131% in January of 2014, reaching 1.1% market share in April when it begins operating its lit ECN. Its market share steadily declines from February of 2016 until August when it begins operating as an exchange. IEX volume share increases from 1.42% to 1.52% in the primary sample period studied in this paper (August–September 2016).

Figure 2 here

Figure 3 Panel A plots average daily market share in terms of the percent of trades, volume, and dollar volume around the exchange transition. Panel B plots average daily time at or inside the NBBO. During the exchange transition IEX loses market share, and market makers quote less often inside the NBBO. After all symbols are phased in on September 2nd, both market share and quote time inside the NBBO increase. In particular, the percent of trades executed on IEX increases from around 1.5% to above 2%. Average time inside the NBBO increases from 21% to 22%.

Figure 3 here

Overall, the protected quote appears to incentivize both traders and liquidity providers to use IEX. Despite the fact that IEX market share is small, it is inside the NBBO nearly one-fifth of the time, even without the protected quote. Once IEX has a protected quote its access delay can no longer be ignored, hence the access delay to its quotes may be in force more often than its small market share would suggest. I examine the effect of IEX's protected quote and access delay on market quality and the efficiency of price discovery in subsequent sections.

3 Market Quality

Table 3 reports estimates of the treatment effects of access delays on market quality. Column 1 reports regressions where the dependent variable is the Quoted Spread. Time-Weighted Average Quoted Spreads increase by 33 mills for the average symbol after IEX begins operations as a national securities exchange.[36] Symbols that traded the most on the IEX ATS experience a 54 mill decrease in quoted spreads relative to symbols that rarely traded on IEX. Column 2 (3) shows that the overall change in Volume-Weighted Effective Spreads and Realized Spreads is statistically indistinguishable from zero. However, high IEX market share symbols experience a decrease in Effective (Realized) Spreads of 24 (26) mills. Column 4 reports regressions where the dependent variable is an Illiquidity Factor which captures the common variation between the three weighted average spread measures, as well as their equal-weighted counterparts. Overall Illiquidity increases by 0.13, but for high IEX market share symbols illiquidity decreases by 0.30 relative to low IEX market share symbols. Point estimates are statistically robust with standard errors clustered by symbol and day.

Table 3 here

Although quoted spreads increase on average, the economic magnitude is small relative to the improvement market quality for high IEX symbols. The results are consistent with reductions in speed preventing market makers from immediately updating their quotes, but mitigating adverse selection from "quote snipers" (e.g., Menkveld and Zoican (2016)). The decrease in effective and realized spreads are unambiguous improvements for high IEX share symbols. Lower effective spreads are consistent with lower trading costs, and lower realized spreads are consistent with lower potential adverse selection costs. Taken together, the evidence appears to support the hypothesis that the speed bump improves market quality–perhaps by deterring quote sniping–but suggests a more nuanced view of the effect of speed on market quality.

[36] A mill is one-hundredth of a cent.

4 The Efficiency of Price Discovery

Table 4 reports estimates of the treatment effects of access delays on the (in)efficiency of price discovery. Column 1 (2) reports regressions where the dependent variable is the Autocorrelation (Variance Ratio) Factor (see 10). Price (In)efficiency, measured by the Autocorrelation (Variance Ratio) Factor, decreases for the average symbol after IEX becomes an exchange, and increases for symbols with high IEX market share relative to symbols with low IEX market share. Column 3 shows that price delays decrease overall, and decrease more for high IEX share symbols relative to symbols with low IEX market share. Column 4 reports regressions where the dependent variable is a Price Discovery (In)efficiency Factor which captures the common variation between the three measures. Overall, the efficiency of price discovery improves, with no difference between high and low IEX market share symbols. The point estimates are statistically robust with standard errors clustered by symbol and day.

Table 4 here

Although return autocorrelations (and variance ratios) increase for high IEX symbols, these symbols experience a net improvement in price discovery. High IEX symbols also experience a large net decrease in price delays (and the Price Discovery Factor). The price discovery results are not predicted by the hypotheses. Therefore, a natural question is whether the improvements in price discovery are attributable to price discovery on IEX. I describe a framework for decomposing price discovery by venue in the next section.

5 Information Shares

De Jong and Schotman (2010) proposes a model of price discovery which generalizes the Hasbrouck (1993) model to a multivariate setting and produces structural estimates analogous to the information shares from Hasbrouck (1995). In the model, observed prices across multiple markets depend on an unobserved efficient price, but are influenced by transient microstructure noise. Formally:

$$\begin{aligned} p_t &= \imath p_t^* + u_t \\ p_t^* &= p_{t-1}^* + r_t, \end{aligned} \tag{2}$$

where p_t is an $N \times 1$ vector of observed log prices, u_t is an $N \times 1$ vector of error terms, p_t^* is the scalar unobserved efficient price, r_t is the innovation in the efficient price, and $\imath$ is an $N \times 1$ vector of ones. The transient microstructure noise vector u_t is correlated with true price innovations, and demonstrates serial dependence: $u_t = \alpha r_t + e_t + \Psi e_{t-1}$, where α is the vector of correlations, e_t is a vector of idiosyncratic noise, and Ψ is an $N \times N$ matrix of coefficients.

Information shares in the model correspond to the partial R^2 of a regression of variation in the efficient price r_t on variations in the observed prices ($\nu_t = p_t - \imath p_{t-1}^*$):

$$r_t = \gamma' \nu_t + \eta_t, \tag{3}$$

where η_t is the innovation in the efficient price orthogonal to innovations in market prices, and γ is the vector of regression coefficients. The overall R^2 is given by:

$$R^2 = 1 - \frac{\sigma_\eta^2}{\sigma_r^2} = \sum_{i=1}^{N} \gamma_i (1 + \alpha_i) \equiv \sum_{i=1}^{N} IS_i, \tag{4}$$

Hence, in the De Jong and Schotman (2010) model, an exchange that explains more variation in the efficient price contributes more to price discovery and has a higher information share.

To estimate the model, I use log midquote prices based on quote updates sampled at one-second intervals from the stock exchanges, as well as from IEX (both ECN and exchange). In order to make the task of estimating the state-space model feasible without sacrificing representativeness, I construct a stratified sample of 90 symbols with 30 symbols from each tercile of Q2 IEX market share. The sample period covers August 29th–September 9th of 2016, which includes the ten days (two trading weeks) surrounding September 2nd, the final day of the Exchange Phase-In. I represent the model in state-space form, and uncover efficient price series for each stock-day using a Kalman Filter. Stock-day maximum likelihood parameter estimates, from which the information shares are computed, are identified using the EM algorithm. Complete details on the state-space model and estimation can be found in the 10.

Figure 4 plots the average information share for each venue. After becoming an exchange, there is no change in IEX's information share (dotted line). Both before and after, IEX hovers around 2.5%. The dominant venues by information share are NYSE Arca, NASDAQ OMX, and BATS.

Figure 4 here

The overall improvement in price discovery in Table 4 cannot be attributed to changes in IEX's information share–or the lack thereof. Instead, the results suggest that the price discovery results may be a cross-market phenomenon. Recent research suggests that algorithmic trading plays an important role in price discovery (e.g., Brogaard et al. (2014, 2015)). In the next section, I examine the usage of Intermarket Sweep Orders (ISOs), which are commonly associated with institutional algorithmic traders.[37]

6 Intermarket Sweep Orders

Does IEX's protected quote and access delay affect the price formation process by changing how institutions trade? In a Comment Letter to the SEC, Citadel raises the concern that "the proposed IEX Access Delay and IEX protected quotation status would [...] interfere with trading and quoting on other venues." In contrast, Virtu comments: "IEX's 'speed bump' has had no impact on Virtu's market making and liquidity provisioning on the platform." In this section I focus on one institutional order type of great practical and regulatory relevance–the Intermarket Sweep Order.

Rule 611 grants nine exceptions to the trade-through requirement. The two most significant exemptions, in terms of trading volume, involve the use of Intermarket Sweep Orders. ISOs are limit orders that are designed to execute against the full displayed size of all protected quotes with superior prices to the ISO. The ISO exception allows any trading center (and registered broker-dealers) to immediately execute a trade at any size and price, so long as it simultaneously routes ISOs to the better priced protected quotes.[38] Hence, although ISOs are "exempted," participants must check all protected quotes including IEX's (potentially delayed) quote–which may impact the use of ISO strategies.[39]

ISO usage may impose negative externalities on price discovery to the extent that they exploit mechanical or regulatory arbitrage opportunities and crowd out fundamental traders. In a Comment Letter responding to

[37] See SEC Equity Market Structure Concept Release, and McInish et al. (2014).

[38] For more on Rule 611, the Order Protection Rule, and its exemptions, refer to the Memorandum from the Division of Trading and Markets.

[39] The FIA Principal Trader's Group raises specific concerns that ISOs interacting with the IEX speed bump may result in more locked or crossed markets. Hence, some institutions may change their ISO strategies to avoid causing locked or crossed markets.

the SEC's Market Structure Concept Release, high-frequency trading firm Tradeworx describes a strategy using ISOs to conduct "order-anticipation."[40] In general, order anticipation involves faster traders predicting the orders of fundamental informed traders and profiting off of their information acquisition.[41] Two forms of order anticipation have been proposed in the theoretical literature. Yang and Zhu (2016) describes "back-running" in which one investor (the back-runner) learns from an informed investor's prior trades and competes for profits in subsequent periods. Baldauf and Mollner (2015) describes a different type of order anticipation in a multi-market setting where a trader simultaneously submits orders to all exchanges, but exchange latencies allow a fast trader to partially observe the signal on one venue and trade ahead on other venues. Regardless of whether order-anticipation happens across space or time, the result is that fundamental informed traders are crowded out of the market, and information is compounded into prices more slowly.

I focus on three aspects of ISO executions. The first and most basic measure is the percentage of trade executions that are ISOs. A more informative measure proxy of ISO usage is the percentage of total Order Volume that are executed as ISOs. The final measure is the ratio of ISO executions to the number of Cancellation messages.[42] Order and message volumes come from the the SEC's MIDAS Metrics website.

Table 5 reports estimates of the treatment effects of access delays on ISOs. Column 1 (2) reports regressions where the dependent variable is the executed ISO Volume divided by the total executed Trade Volume (total submitted Order Volume). The ISO/Trade (ISO/Order) ratio decreases for the average symbol after IEX becomes an exchange. Symbols with higher IEX market share tend to see less ISOs on average. The dependent variable in Column 3 is the number of ISO messages divided by the number of Cancellation messages. Similar to the ISO Volume ratios, the number of ISO messages, relative to the number of cancel messages decreases after IEX receives a protected quote. In all three Columns the point estimate on the interaction term is indistinguishable from zero.

[40] `https://www.sec.gov/comments/s7-02-10/s70210-129.pdf`

[41] Order anticipation is not necessarily harmful or illegal. Front-running, which is a distinct form of order anticipation, is illegal.

[42] I exclude ISO executions on IEX for the third measure because the IEX TOPs feed does not disseminate cancel messages.

Table 5 here

The observation that ISO executions decrease overall is consistent with institutions changing their ISO strategies. Despite concerns over the interaction of ISOs with the speed bump, institutions do not appear to be adjusting their strategy specifically for stocks with higher IEX market share. Finally, the change in ISO executions appears to coincide with improvements with price discovery (see Table 4) but not market quality (Table 3). This is consistent with claims that ISOs are an important part of certain order anticipation strategies. The results are also broadly consistent with recent evidence on the negative externalities of algorithmic trading patterns which may involve order anticipation (Weller, 2015; Sağlam, 2016).

7 IEX Goes Dark

Granting IEX a protected quote appears to improve certain aspects of market quality and price discovery–however an important unanswered question is whether its speed bump is suitable for other exchanges, given its market structure design as dark pool. In his Comment Letter to the Commission, Charles Jones argues that IEX favors dark over lit liquidity, and cites his prior work showing that market conditions worsened when the Island ECN went dark (Hendershott and Jones, 2005). He considers a hypothetical version of IEX where pegged orders may be displayed or non-displayed. On this hypothetical exchange a displayed pegged order is executed at the NBBO 350 milliseconds later than the same order with non-displayed status. Using recent NASDAQ market share and direct feed data, Jones estimates an annual "subsidy" to using non-displayed orders of $400 million.

However, IEX's effective execution priority may not be biased towards dark liquidity for three important reasons. First, IEX does not offer displayed pegged orders, all pegged orders are non-displayed.[43] Second, IEX executes orders with price-display-time priority which means that resting lit orders execute first–relative to dark orders–against incoming marketable orders at the same price level.[44] Third, IEX "subsidizes" *displayed* orders relative to

[43]NASDAQ offers displayed and non-displayed pegged orders, hence the example may also be thought of as a hypothetical version of NASDAQ where displayed orders are picked off at stale prices (see Themis Trading Comment Letter).

[44]See IEX Rule 11.220.

non-displayed orders as it does not charge to post or take displayed liquidity, but charges a fee to match non-displayed orders.

Nevertheless, Jones' concern is important as other venues could adopt speed bumps which prioritize dark liquidity.[45] To address the claim that prioritizing dark orders "may be bad for overall market liquidity" and lead to "less timely price discovery market-wide," I exploit the fact that IEX goes dark for several symbols during its time as an ECN. Like Island, IEX goes dark rather than publish its quotes for contribution to the NBBO as required by Rule 301(b)(3) of Reg ATS. The reporting obligations apply to any ATS that:

> (a) displays subscriber orders to any person (other than alternative trading system employees); and (b) during at least 4 of the preceding 6 calendar months, had an average trading volume of 5 percent or more of the aggregate average daily share volume for [an] NMS stock...

Island complies by displaying no quotes, whereas IEX complies by refusing to accept displayed orders. Therefore, when IEX goes dark its matching engine effectively ranks all interest marked for display behind non-displayed interest at any price or time.

In order to quantify the effect of IEX prioritizing dark liquidity, I identify periods where IEX's reported average daily trading volume is at least 5% for 4 of the 6 preceding months, consistent with Reg ATS. As with Island, the effect of going dark is temporary–once IEX is under the threshold it resumes accepting displayed orders. The 28 symbols that go dark (the treatment group), and their respective dark/lit dates are listed in Table 6. In addition, I identify a set of 66 symbols that reach an average daily trading volume of at least 5% for 3 of the 6 preceding months but never go dark to use as a control group.

Table 6 here

Using the sample of treatment and control symbols I run regressions of the form:

$$y_{i,t} = \beta_0 + \beta_1 Dark + \beta_2 X_{i,t} + \varepsilon_{i,t}, \tag{5}$$

[45]NYSE American also maintains price-display-time priority with a speed bump, but may indirectly "subsidize" dark liquidity by allowing its Designated Market Makers to post non-displayed orders for free.

where *Dark* is a (0,1) indicator for when a symbol goes dark. $X_{i,t}$ includes a full set of group and month dummy variables.

Table 7 reports estimates of the treatment effect of IEX going dark on market share, market quality, and the efficiency of price discovery. When Island goes dark, market share, market quality, and the efficiency of price discovery all decline (see Hendershott and Jones (2005)). In contrast, Panel A shows that when IEX goes dark, there is no change in market share, market quality, or price discovery.

Table 7 here

The stark difference between Island and IEX is likely due to the fact that IEX market share is much smaller than Island had at the time. In addition, matched volume against displayed liquidity accounts for less than 10% of overall IEX volume, whereas when Island went dark 100% of its displayed liquidity became dark. Finally, Island also goes dark before Regulation NMS, which decentralized trading and price discovery across multiple exchanges.

8 Robustness

In the main results, I partition the sample by IEX market share under the working hypothesis that stocks with higher IEX market share should experience access delays more often than stocks with low IEX market share. However, an alternative, approach is to partition symbols based on the amount of time IEX's quotes are inside the NBBO. If IEX has competitive quotes, then Rule 611 obligates other venues to cancel trades at inferior prices, or to route orders to IEX. Hence, when IEX is inside the NBBO market participants are more likely to encounter its speed bump. Specifically, I use the average time inside the NBBO over Q2 of 2016 from IEX's ECN.

Table 8 Panel A reports estimates of the treatment effects of access delays on market quality, conditional on time inside the NBBO. Time-Weighted Average Quoted Spreads increase by 28 mills for the average symbol after IEX begins operations as a national securities exchange. Symbols where IEX ECN quotes are frequently inside the NBBO experience a 33 mill decrease in quoted spreads relative to symbols where IEX is rarely inside the NBBO. Column 4 reports regressions where the dependent variable is an Illiquidity Factor which captures the common variation between the three weighted average spread measures, as well as their equal-weighted counterparts. Overall Illiquidity increases by 0.11, but the point estimate is indistinguishable from zero. For symbols where IEX quotes are frequently inside the NBBO, illiquidity decreases by 0.17 relative to low IEX market share symbols.

Panel B reports estimates of the treatment effects of access delays on the (in)efficiency of price discovery, conditional on time inside the NBBO. Columns 1–4 reports regressions where the dependent variable is the Autocorrelation (Variance Ratio, Price Delay, and Inefficiency) Factor. The efficiency of price discovery improves across all measures after IEX becomes an exchange, and improves more for symbols where IEX frequently quotes inside the NBBO relative to symbols where IEX rarely quotes inside the NBBO.

Table 8 here

Overall, the estimates in Table 8 are nearly identical to the main results. Notably, symbols where IEX quotes are frequently inside the NBBO have significantly higher liquidity and superior price discovery across the board. In contrast, stocks with high IEX market share tend to have inefficient price discovery on average (Table 4).

9 Conclusion

Market participants and academics are once again calling for regulators to conduct a holistic review of Regulation NMS. Market participants, including members of the SEC's Equity Market Structure Advisory Committee have also raised the possibility of eliminating Rule 611 altogether. In academia, Pagnotta and Philippon (2016) argues that Rule 611 results in fragmented markets characterized by high speed but low allocative efficiency. To address negative externalities resulting from the new "high-frequency market structure," Budish et al. (2015) argues that the SEC ought to overhaul Regulation National Market System entirely and replace continuous limit order books with discrete-time batch auctions (see also Budish et al. (2014)). Biais et al. (2015) proposes "slow markets" as a potential market solution to the high-frequency arms race (see also Biais and Foucault (2014)). However, the solution may be–as Chair White has suggested–to allow exchanges to compete and innovate to deemphasize speed. Given the new interpretation of

Rule 611, perhaps the most important question is "Will the Market Fix the Market?" (Budish et al., 2017). To answer this question regulators will need empirical evidence to make data-driven policy decisions.

As a first step, this study provides empirical evidence that deemphasizing speed using intentional access may improve market quality and price discovery. In particular, the IEX market structure appears to work as a "slow market," and although it does not contribute more to price discovery as an exchange than as an ATS, its dark pool features do not appear to harm pre-trade transparency. Hence, the preliminary evidence suggests that market solutions to deemphasize speed may be a feasible alternative to regulatory intervention.

The broader implications of the new interpretation of Rule 611 are yet to be seen. The SEC's interpretation of the "immediate access" requirement of Rule 611 to permit *de minimis* access delays essentially allows trading venues to compete for order flow from investors with different speed requirements. However, this interpretation does not constitute a blank check for new access delays and order types. Based on the evidence presented in this paper that *de minimis* access delays can have non-trivial effects on market quality and price discovery, this paper supports Commission staff carefully reviewing each proposal to ensure that trading venues are able to innovate successfully to deemphasize speed without harming market efficiency. I discuss several recent proposals in Appendix A3.

Appendix

A1 Informational Efficiency Measures

All three informational efficiency measures are based on NBBO midquote returns, measured at different intervals. Midquote returns are preferable to transaction prices because they do not suffer from bid-ask bounce volatility. Prevailing midquotes matched to trades provide similar results but may be affected by heterogeneities in trading frequencies (see Chordia et al. (2008)).

Positive or negative autocorrelations in midquote returns imply informational inefficiency. As in Comerton-Forde and Putniņš (2015), I compute absolute first-order autocorrelations for each stock-day at $k \in \{10, 30, 60\}$ second intervals:

$$AutoCorrelation_k = Corr(r_{k,t}, r_{k,t-1}), \tag{6}$$

where $r_{k,t}$ is the t-th midquote return of length k for a stock-day. I take the first principal component of the three frequencies to construct an Autocorrelation Factor. I scale the factor on a [0,1] interval, where larger values indicate high inefficiency.

If prices follow a random walk, the variance of the returns should be linear in the measurement frequency, i.e., σ_k^2 is k times larger than σ_1^2. I compute Variance Ratios for three frequency pairs– (1,10), (10,60), and (60,300)– measured in seconds:

$$VarianceRatio_{kl} = \left| \frac{\sigma_{kl}^2}{k\sigma_l^2} - 1 \right|, \tag{7}$$

where σ_l^2 and σ_{kl}^2 are the variances of l-second and kl-second midquote returns for a given stock-day. I take the first principal component of the three frequency pairs to construct a Variance Ratio Factor. I scale the factor on a [0,1] interval, where larger values indicate high inefficiency.

Hou and Moskowitz (2005) introduces a measure of market frictions termed "price delays." I construct a high-frequency version of the price delay measure which captures the extent to which lagged market-wide information predicts stock returns. For each stock-day, I estimate a regression of one-minute midquote returns, $r_{i,t}$, on the SP500 ETF market return (SPY), $r_{m,t}$, and ten lags:

$$r_{i,t} = \alpha_i + \beta_i r_{m,t} + \sum_{k=1}^{10} \delta_{i,k} r_{m,t-k} + \varepsilon_{i,t}. \quad (8)$$

I use the R^2 of the above regression ($R^2_{Unconstrained}$) and the constrained version with no lags ($R^2_{Constrained}$) in order to compute the delay measure:

$$Delay = 1 - \frac{R^2_{Constrained}}{R^2_{Unconstrained}}. \quad (9)$$

The Price Delay measure takes on values between 0 and 1, where larger values indicate high inefficiency.

A2 De Jong and Schotman (2010) model in state-space form

Model

Ozturk et al. (2017) describes how to represent the De Jong and Schotman (2010) model in state-space form, which identifies the unobserved efficient price using a Kalman Filter, and maximum likelihood estimates of the model parameters (including the information shares) using the Expectations Maximization (EM) algorithm.

The Kalman Filter is well-suited for dealing with high-frequency financial data for several reasons. First, the Kalman Filter uses not only past information (filtering), but also future information (via smoothing) to determine the efficient state. While future information is normally eschewed to avoid "look-ahead biases," it is essential in determining whether price changes are permanent or transitory. Second, multi-market trading and quoting activity fit naturally in a multivariate state-space model. Third, the Kalman Filter deals with missing observations, for instance when quotes do not overlap.[46]

[46] Hendershott et al. (2013) and Menkveld et al. (2007) discuss the use of state space models for financial data in more detail. For other example applications of state space models in microstructure see Hendershott and Menkveld (2014), Menkveld (2013), and Brogaard et al. (2014). For a general treatment on Kalman Filtering for time-series modelling see Durbin and Koopman (2012).

The state space form of Equation 2 can be written:

$$p_t = \begin{bmatrix} \imath_{N\times 1} & \alpha & \Psi \end{bmatrix} \begin{bmatrix} p_t^* \\ r_t \\ e_{t-1} \end{bmatrix} + G\varepsilon_t, \text{ where } G = \begin{bmatrix} 0_{N\times 1} & I_N \end{bmatrix} \text{ and } \varepsilon_t = \begin{bmatrix} r_{t+1} \\ e_t \end{bmatrix}, \tag{10}$$

$$\begin{bmatrix} p_{t+1}^* \\ r_{t+1} \\ e_t \end{bmatrix} = \begin{bmatrix} 1 & 0_{1\times N+1} \\ 0_{N+1\times 1} & 0_{N+1\times N+1} \end{bmatrix} \begin{bmatrix} p_t^* \\ r_t \\ e_{t-1} \end{bmatrix} + H\varepsilon_t, \text{ where } H = \begin{bmatrix} \imath_{2\times 1} & 0_{2\times N} \\ 0_{N\times 1} & I_N \end{bmatrix}, \tag{11}$$

where $\imath_{n\times m}$ is an $n \times m$ matrix or vector of ones, $0_{n\times m}$ is an $n \times m$ matrix or vector of zeros, Ψ is an $N \times N$ matrix, and I_N is an $N \times N$ identity matrix. Equation 10 is the observation equation, and Equation 11 is the state equation. The covariance matrix of the error terms $\begin{bmatrix} H & G \end{bmatrix}' \varepsilon_t$ is given as:

$$E\left[\begin{bmatrix} H \\ G \end{bmatrix} \varepsilon_t \varepsilon_t' \begin{bmatrix} H \\ G \end{bmatrix}' \right] = \begin{bmatrix} \sigma_r^2 \imath_{2\times 2} & 0_{2\times N} & 0_{2\times N} \\ 0_{N\times 2} & \Omega & \Omega \\ 0_{N\times 2} & \Omega & \Omega \end{bmatrix}. \tag{12}$$

Estimation

Each stock-day sample consists of one second interval top of book quote midpoints from the exchanges and IEX from between the hours of 9:00 AM to 4:30 PM. The quote midpoints include all quotes which are not crossed or locked.

To obtain maximum-likelihood estimates of the model in Equations 10 and 11 I use the Kalman Filter Expectations Maximization algorithm. The first step, the "E Step," involves Kalman Filtering and Smoothing to uncover the state vector $\begin{bmatrix} p_{t+1}^* & r_{t+1} & e_t \end{bmatrix}'$ given estimates of the transition and covariance matrices. The "M Step" estimates the transition and covariance matrices by maximizing the expected log-likelihood using the new state estimates. Each iteration of the EM algorithm is $O(Tnd^3)$ where T is the number of time steps, n is the number of iterations, and d is the size of the state space. I use ten iterations of the EM algorithm to minimize computational complexity while assuring convergence of the likelihood estimates.

A3 Other Exchange Proposals

NYSE

In June 2016, the SEC approved NYSE Arca's proposed Discretionary Peg (DPEG) order, which is based on the IEX DPEG order.[47] Like IEX, NYSE Arca's novel pegged orders rest at the inside of the NBBO, do not execute during "crumbling quote" periods, and can seek liquidity at the midpoint.[48] Crumbling quote periods are determined by a logistic regression formula which tries to predict changes in the NBBO. However, IEX argues that the NYSE Arca DPEG may not achieve the intended effects of protecting investors from crumbling quotes because i) IEX's algorithm (logistic regression) is calibrated for its specific data center latencies, and ii) the NYSE offers co-location and direct feed services which advantage fast traders. Additionally, NYSE Arca does not have a speed bump. IEX's speed bump is designed to ensure that the exchange has time to re-price its pegged orders before high-frequency traders are able to pick off stale quotes. Therefore, it is not clear whether the lack of a speed bump or presence of other market structure features (e.g., co-location) will impact the efficacy of NYSE Arca's crumbling quote protection.

In January of 2017, NYSE announced it would file for approval to convert its NYSE MKT floor cash equities exchange to a fully automated electronic exchange–rebranded as NYSE American–with a DPEG, and a 350-microsecond speed bump on incoming orders and outbound data and external routing.[49] NYSE American may provide an interesting comparison to IEX and NYSE Arca in that it blends market structure features from both. With a 350-microsecond speed bump and DPEG orders, NYSE American is similar to IEX. Of course, NYSE American is based on the same Pillar electronic trading platform as NYSE Arca.[50] NYSE American also offers co-location,

[47] `https://www.sec.gov/rules/sro/nysearca/2016/34-78181.pdf`

[48] See IEX's Order Types, for example `https://www.iextrading.com/trading/order-types/`. IEX's DPEG and Primary Peg correspond to the NYSE Arca Discretionary Pegged Order (DPO) and Dark Primary Peg (DPP), respectively. DPEG and DPO have midpoint discretion.

[49] See `https://www.sec.gov/rules/sro/nysemkt/2017/34-79998.pdf`, `https://www.sec.gov/comments/sr-nysemkt-2017-05/nysemkt201705.htm`, and, `https://www.sec.gov/rules/sro/nysemkt/2017/34-81115.pdf`.

[50] NYSE MKT was a floor cash equities exchange. See also: Functional Differences Between NYSE Arca Pillar and NYSE American Pillar.

charges for direct feed access, and pays rebates to designated market makers. Cross-sectional differences between NYSE American, Arca, and IEX may be useful in comparing the efficacy of DPEG orders in preventing executions during periods of high transitory volatility. However, its (re-)launch may not be a useful natural experiment for identifying the effects of a speed bump because the NBBO already includes IEX's "slow" quote, and because of the significant market structure changes as NYSE MKT transitions to NYSE American.[51]

NASDAQ

On November 30, 2016 NASDAQ proposed a new "extended-life order" (ELO) type with a minimum resting time (no cancellations or alterations) of one second.[52] The proposal sought to give ELOs execution priority over other displayed orders at the same price. The SEC approved the ELO proposal on July 7, 2017.[53] Although different from a speed bump, the ELO was designed to cater to "long-term investors" focusing on designated retail orders. Hudson River Trading and Citadel argued that ELOs discriminate against limit orders from traditional market makers. Harris (2013) argued that minimum resting time policies would increase intermediation costs for high-frequency market makers, without helping traditional market makers avoid adverse selection. In contrast, BATS and Themis Trading expressed support for ELOs, with some reservations about NASDAQ's implementation. Aït-Sahalia and Saglam (2013) argued that mandatory minimum resting times may induce high-frequency market makers to provide liquidity more often. NASDAQ's ELOs are optional, therefore it is not clear whether they would help or harm liquidity. In addition, it is unclear if retail investors would be interested in ELOs, given that most retail order flow is internalized.[54]

[51]Apart from the technological changes of the Pillar platform, NYSE American also changes its fees and order type offerings c.f. https://www.nyse.com/publicdocs/nyse/markets/nyse-american/NYSE_MKT_Equities_Price_List.pdf.

[52]See https://www.sec.gov/rules/sro/nasdaq/2016/34-79428.pdf.

[53]See https://www.sec.gov/rules/sro/nasdaq/2017/34-81097.pdf.

[54]https://www.sec.gov/spotlight/equity-market-structure/issues-affecting-customers-emsac-012616.pdf

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Tables and Figures

Table 1: **Hypotheses**

Hypothesis	Market Quality	Price Discovery
H0	-	-
H1A	↓	↓
H1B	↑	-

Table 2: **Summary Statistics.** Panel A summarizes the main variables of interest for the period August 1st–August 18th just before the IEX Exchange Phase-in. Quoted Spreads are based on all valid NBBO quotes. Effective and Realized Spreads are based on all valid trades matched to NBBO quotes. The (Il)liquidity factor is the first principal component of the spread measures. Autocorrelation, Variance Ratio, and Price Delay measures are defined in The Appendix. The Price Discovery (In)efficiency factor is the first principal component of the price discovery measures. IEX Share is based on the total number of trades. Time at or inside the NBBO is based on IEX top of book quotes and NBBO quotes. Panel B presents a more detailed view of IEX activity over Q2 of 2016. An odd lot is a trade of less than 100 shares. A block is defined as a trade of at least 10,000 shares or $200,000.

(a) Main Variables

	Mean	SD	Q1	Med.	Q3
QuotedSpread	0.116	0.194	0.021	0.049	0.122
EffectiveSpread	0.076	0.125	0.015	0.033	0.078
RealizedSpread	0.053	0.099	0.005	0.018	0.053
(Il)liquidity	0.080	0.128	0.016	0.035	0.083
Autocorrelation	0.126	0.072	0.075	0.104	0.154
VarianceRatio	0.276	0.069	0.227	0.289	0.337
PriceDelay	0.584	0.299	0.299	0.657	0.878
(In)efficiency	0.411	0.139	0.295	0.428	0.526
IEXShare	0.012	0.009	0.005	0.012	0.017
At NBBO	0.195	0.253	0.000	0.080	0.294

(b) IEX Q2 Statistics

	Mean	SD	Q1	Med.	Q3
# of Trades	4,322	11,809	54	436	3,202
Vol.	929,113	3,293,237	7,239	73,753	580,617
Vol. ($)	37 MM	177 MM	92 K	1 MM	12 MM
Avg. Size	172	109	116	152	199
Avg. Size ($)	4,568	6,023	1,438	2,806	5,799
# of Blocks	33	166	2	6	23
Block Vol.	235,569	605,097	20,000	59,542	200,058
Block Vol. ($)	12 MM	59 MM	430 K	1 MM	7 MM
# Odd Lots	338	770	10	78	299
Odd Lot Vol.	10,691	24,550	263	1,905	9,044
Odd Lot Vol. ($)	829 K	5 MM	3 K	28 K	218 K
In NBB	8.68%	13.99%	0.00%	0.67%	12.54%
In NBO	8.67%	13.91%	0.00%	0.77%	12.68%
In NBBO	15.64%	23.69%	0.00%	1.47%	24.62%

Table 3: **Market Quality Regressions.** The sample includes all traded symbols in August and September of 2016 with valid trade data, quote data, and daily MIDAS statistics. Protected Quote refers to a binary indicator variable which is one when IEX begins trading the symbol on its exchange (see Figure 1). IEX Market Share is based on the percentage of trades. The Illiquidity Factor is the first principal component of the three spread measures. Larger values indicate worse market quality. Standard errors are clustered by symbol and date.

	(1) QSpread	(2) ESpread	(3) RSpread	(4) Illiquidity
Protected Quote	0.329**	0.122	0.0279	0.133*
	(2.66)	(1.40)	(0.46)	(1.83)
IEX Market Share	-0.360	-0.589***	-0.398**	-0.457**
	(-1.25)	(-3.09)	(-2.60)	(-2.36)
P.Quote × IEX Sh.	-0.545***	-0.236***	-0.257***	-0.301***
	(-5.10)	(-2.94)	(-4.08)	(-4.30)
(Cancel/Trade)/1000	0.219**	0.199***	0.174***	0.201***
	(2.31)	(3.02)	(3.35)	(3.01)
Trade/Order	-113.1***	-65.07***	-42.31***	-67.51***
	(-7.57)	(-6.38)	(-5.33)	(-6.64)
Odd/Trade	54.79***	32.73***	23.58***	34.16***
	(20.7)	(18.1)	(16.1)	(18.8)
Market Cap Rank	-1.100***	-0.695***	-0.710***	-0.809***
	(-8.37)	(-6.67)	(-8.34)	(-8.02)
Volatility Rank	0.482***	0.283***	0.146**	0.271***
	(4.09)	(3.35)	(2.13)	(3.23)
Turnover Rank	-0.585***	-0.398***	-0.422***	-0.455***
	(-5.75)	(-5.39)	(-7.14)	(-6.26)
R^2	0.27	0.23	0.21	0.26

Table 4: **Price Discovery Regressions.** The Price Discovery variables in Columns 1–3 are defined in the Appendix. The Inefficiency Factor is the first principal component of the Price Discovery variables. Larger values indicate less efficient price discovery. Standard errors are clustered by symbol and date.

	(1) Autocorr	(2) VarianceRatio	(3) Delay	(4) Inefficiency
Protected Quote	-0.727***	-1.233***	-7.143***	-2.855***
	(-5.21)	(-4.87)	(-4.54)	(-4.95)
IEX Market Share	-0.533***	0.674***	6.818***	1.647***
	(-5.04)	(7.68)	(14.4)	(9.17)
P.Quote × IEX Sh.	0.295***	0.0577*	-1.802***	-0.134
	(3.40)	(1.71)	(-4.07)	(-1.44)
(Cancel/Trade)/1000	-0.0882***	-0.261***	-1.820***	-0.628***
	(-3.55)	(-12.3)	(-9.86)	(-11.9)
Trade/Order	8.448*	94.61***	705.6***	226.8***
	(1.86)	(16.6)	(27.2)	(21.3)
Odd/Trade	7.062***	13.36***	58.35***	27.18***
	(12.8)	(23.5)	(24.6)	(26.1)
Market Cap Rank	-0.849***	-1.820***	-6.863***	-3.405***
	(-25.7)	(-44.1)	(-36.4)	(-44.6)
Volatility Rank	-0.146***	-0.00462	0.941***	0.0958
	(-4.53)	(-0.17)	(6.83)	(1.66)
Turnover Rank	-0.568***	-0.630***	-2.450***	-1.325***
	(-21.0)	(-22.2)	(-16.0)	(-23.6)
R^2	0.13	0.56	0.45	0.54

Table 5: **ISO Regressions.** ISO/Trade is the ratio of executed ISO volume to total executed volume. ISO/Order is the ratio of executed ISO volume to total order volume from MIDAS. ISO/Cancel is the ratio of the number of ISO executions to the number of cancel messages from MIDAS. Standard errors are clustered by symbol and date.

	(1) ISO/Trade	(2) ISO/Order	(3) ISO/Cancel
Protected Quote	-2.725***	-0.219***	-0.251**
	(-3.87)	(-2.86)	(-2.59)
IEX Market Share	-0.619***	-0.0652**	-0.00719
	(-2.72)	(-2.46)	(-0.14)
P.Quote × IEX Sh.	0.158	0.0101	-0.115
	(0.51)	(0.37)	(-1.42)
(Cancel/Trade)/1000	0.0124	-0.0301***	-0.0475***
	(0.19)	(-7.24)	(-6.36)
Trade/Order	159.4***	62.68***	91.39***
	(14.4)	(26.8)	(21.0)
Odd/Trade	2.201	0.533***	-0.823**
	(1.52)	(4.94)	(-2.34)
Market Cap Rank	1.138***	-0.0303***	0.0515*
	(14.3)	(-3.61)	(1.95)
Volatility Rank	0.813***	0.0404***	0.104***
	(13.6)	(5.06)	(6.53)
Turnover Rank	0.0789	-0.0396***	-0.0174
	(1.30)	(-4.40)	(-0.71)
R^2	0.080	0.21	0.052

Table 6: **Symbols that went dark on IEX's ECN.** Dark Date is the first trading day for which IEX meets the 5% Regulation ATS display threshold and stops accepting displayed orders. Lit Date is the first trading day for which IEX drops below the 5% threshold. EGIF (starred) remains above the threshold in September of 2016, but IEX completes its exchange transition on September 2nd and begins accepting displayed orders for EGIF again.

Symbol	Dark Date	Lit Date
NWHM	2015-05-01	2015-09-01
CABO WI	2015-06-01	2015-07-01
VUSE	2015-06-01	2015-12-01
SIM	2015-07-01	2015-08-01
FLRT	2015-08-01	2015-11-01
CIGI	2015-10-01	2016-02-01
JJM	2015-10-01	2015-12-01
CXRX	2015-11-01	2016-03-01
FSV	2015-11-01	2016-03-01
IBCC	2015-12-01	2016-03-01
BSCN	2016-01-01	2016-02-01
CRTO	2016-02-01	2016-09-01
EET	2016-02-01	2016-05-01
IBCE	2016-02-01	2016-09-01
IGU	2016-02-01	2016-05-01
KOF	2016-02-01	2016-04-01
IBMK	2016-03-01	2016-06-01
EGIF	2016-04-01	2016-09-02*
ITRN	2016-04-01	2016-06-01
EXFO	2016-05-01	2016-07-01
HGG	2016-05-01	2016-06-01
TIER	2016-05-01	2016-07-01
GLYC	2016-06-01	2016-08-01
TDTF	2016-06-01	2016-09-01
STRL	2016-07-01	2016-08-01
TPHS	2016-07-01	2016-09-01
USLB	2016-07-01	2016-08-01
HGG	2016-08-01	2016-09-01
IDLB	2016-08-01	2016-09-01

Table 7: **The effects of IEX going dark.** The sample includes 28 treatment group symbols, listed in Table 6, and 66 control symbols. Dark is a binary variable which is one when IEX's reported average daily trading volume is at least 5% for 4 of the 6 preceding months, consistent with Reg ATS, and zero otherwise. Control group symbols reach an average daily trading volume of at least 5% for 3 of the 6 preceding months but never go dark. The sample period covers all of IEX's ECN operations (April 2014–September 2016).

(a) Market Share Regressions

	(1) % Trades	(2) % Volume	(3) %$ Volume
Dark	0.585 (1.05)	0.702 (1.27)	0.685 (1.29)
R^2	0.087	0.057	0.056

(b) Market Quality Regressions

	(1) QSpread	(2) ESpread	(3) RSpread	(4) Illiquidity
Dark	0.950 (0.29)	0.929 (0.41)	1.027 (0.52)	0.129 (0.43)
R^2	0.0029	0.0028	0.0029	0.0026

(c) Price Discovery Regressions

	(1) Autocorr	(2) VarianceRatio	(3) Delay	(4) Inefficiency
Dark	1.163 (1.34)	0.542 (0.27)	-1.134 (-0.26)	0.611 (0.25)
R^2	0.0053	0.028	0.033	0.033

Table 8: **Inside the NBBO.** Panel A (B) repeats Table 3 (4), defining treatment and control groups based on IEX's time inside the NBBO. Panel C examines IEX market share. Standard errors are clustered by symbol and date.

(a) Market Quality

	(1) QSpread	(2) ESpread	(3) RSpread	(4) Illiquidity
Protected Quote	0.277**	0.101	0.00271	0.106
	(2.24)	(1.20)	(0.046)	(1.48)
Inside NBBO	-2.596***	-1.837***	-1.562***	-1.903***
	(-11.3)	(-11.5)	(-12.2)	(-12.0)
P. Quote x In NBBO	-0.328***	-0.121	-0.131**	-0.170**
	(-3.44)	(-1.61)	(-2.02)	(-2.60)
(Cancel/Trade)/1000	0.165*	0.165**	0.144***	0.164**
	(1.82)	(2.61)	(2.91)	(2.57)
Trade/Order	-113.4***	-66.61***	-43.24***	-68.48***
	(-7.80)	(-6.64)	(-5.57)	(-6.89)
Odd/Trade	52.03***	30.75***	21.91***	32.13***
	(19.7)	(16.8)	(14.9)	(17.6)
Market Cap Rank	-0.811***	-0.524***	-0.555***	-0.616***
	(-6.34)	(-5.06)	(-6.57)	(-6.20)
Volatility Rank	0.452***	0.262***	0.128*	0.249***
	(3.90)	(3.17)	(1.91)	(3.04)
Turnover Rank	-0.426***	-0.292***	-0.329***	-0.342***
	(-4.35)	(-4.18)	(-5.93)	(-4.96)
R^2	0.28	0.24	0.22	0.27

(b) Price Discovery

	(1) Autocorr	(2) VarianceRatio	(3) Delay	(4) Inefficiency
Protected Quote	-0.698***	-1.207***	-7.332***	-2.854***
	(-5.25)	(-4.84)	(-4.55)	(-4.95)
Inside NBBO	-1.381***	-1.059***	-2.420***	-2.119***
	(-14.8)	(-11.0)	(-4.93)	(-11.3)
P. Quote x In NBBO	0.266***	-0.180***	-1.382***	-0.289**
	(3.89)	(-3.50)	(-3.70)	(-2.67)
(Cancel/Trade)/1000	-0.112***	-0.293***	-1.946***	-0.693***
	(-4.57)	(-13.1)	(-9.60)	(-11.7)
Trade/Order	7.699*	99.46***	737.1***	237.6***
	(1.73)	(17.1)	(27.6)	(22.0)
Odd/Trade	5.752***	12.47***	57.23***	25.52***
	(10.6)	(22.4)	(23.8)	(25.0)
Market Cap Rank	-0.727***	-1.607***	-5.876***	-2.965***
	(-22.4)	(-39.9)	(-30.9)	(-39.6)
Volatility Rank	-0.159***	-0.0192	0.891***	0.0658
	(-5.04)	(-0.73)	(6.58)	(1.20)
Turnover Rank	-0.497***	-0.553***	-2.200***	-1.173***
	(-18.6)	(-20.1)	(-14.5)	(-21.6)
R^2	0.14	0.57	0.44	0.54

Fri, Aug 19 – Fri, Sep 2
Exchange Launch Date, Phase-in Period Begins; TOPS v1.5 Phase-in Begins

- *Fri, Aug 19*
  Two non-test securities (VG, WIN)
- *Wed, Aug 24*
  Ten non-test securities (VALE.P, VG, VHC, VIAV, VIP, VLY, WIN, XOMA, YINN, ZIOP)
- *Mon, Aug 29*
  All symbols starting with 'Y' - 'Z', VALE.P, VG, VHC, VIAV, VIP, VLY, WIN, XOMA
- *Wed, Aug 31*
  All symbols starting with 'V' - 'Z'
- *Fri, Sep 2*
  All symbols ('A' - 'Z')

Fri, Sep 2
Exchange Phase-in Period ends, ATS Ceases Operation

Figure 1: **IEX Exchange Phase-in Timeline**

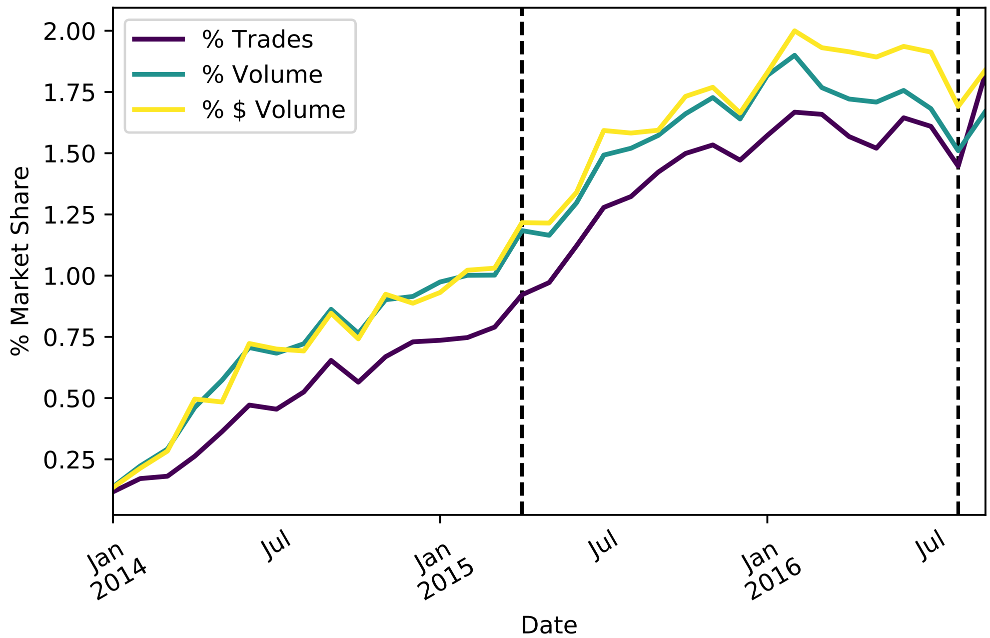
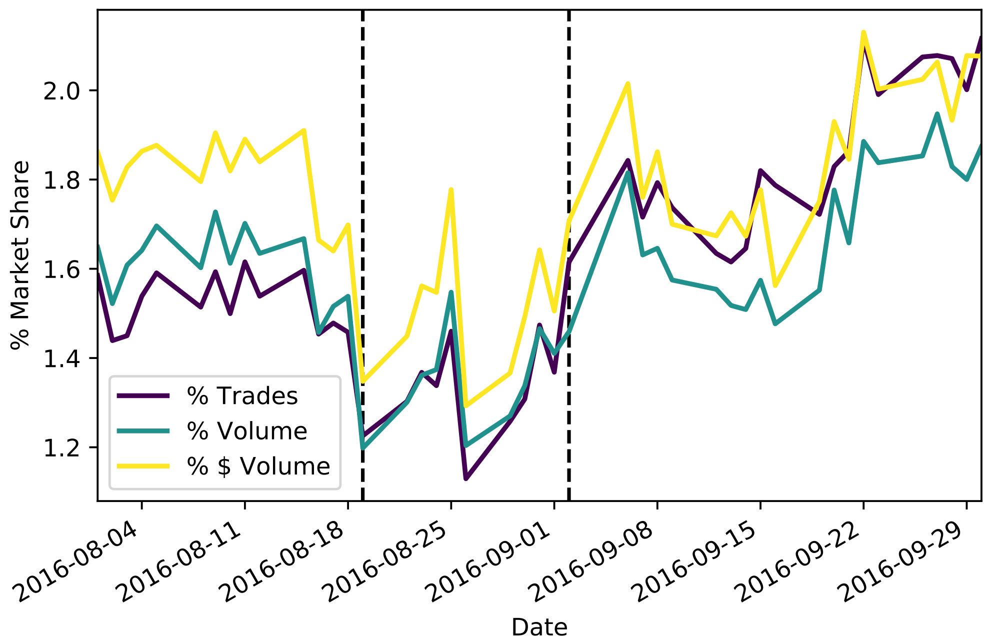


Figure 2: **IEX Market Share (% of Volume) from January of 2014 to September of 2016.** IEX opens its lit ECN in April of 2014. IEX becomes an exchange in August–September of 2016. The first vertical dotted line coincides with the IEX ECN launch, the second marks the beginning of the IEX Exchange Phase-in.

(a) Market Share



(b) Time Inside the NBBO

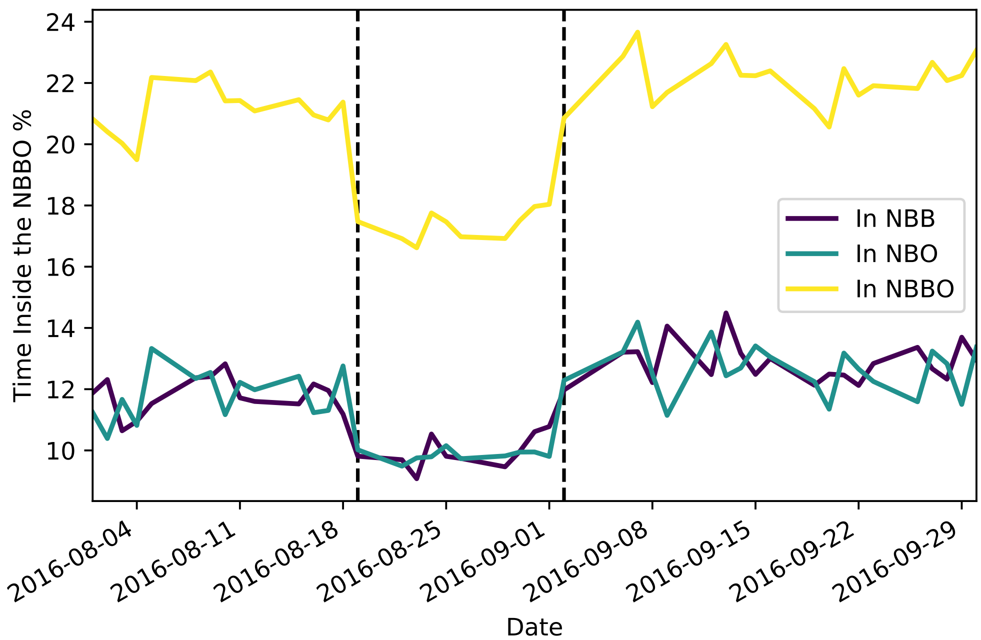


Figure 3: **IEX Market Share During the Exchange Transition.** Market share is based on all valid trades on IEX. Time at or inside the NBBO is based on all valid IEX top of book quotes and NBBO quotes. The vertical dotted lines indicate the start and end of the exchange phase-in.

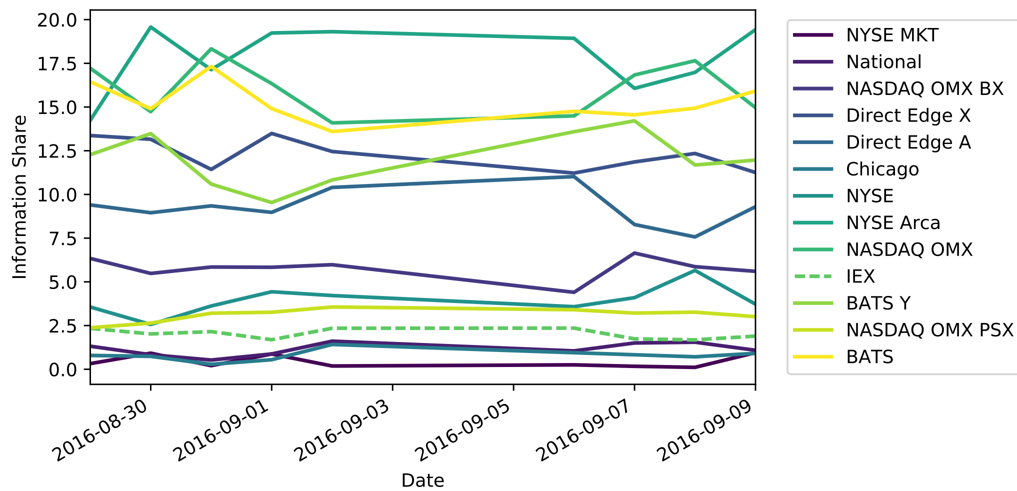


Figure 4: **Information shares during IEX Exchange Transition.** Information shares are based on the De Jong and Schotman (2010) model. IEX's information share is shown using a dotted line. The sample consists of 90 stocks, 30 from each of the three terciles of average daily IEX Market Share over Q2 of 2016. Details of the state-space model and estimation are in the Appendix.