Exchange Competition with Levelled Speed

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Abstract

Technological innovations in the securities exchange industry have facilitated high speed trading and created speed hierarchies among participants. We show that a securities exchange can gain competitive advantage by adopting a speed bump technology that increases latency and improves the market quality for traded stocks by creating a level playing field. Throttled speed curbs excessive follow-on orders, quote-to-trade ratio, and flickering quotes. Meanwhile, extant competing exchanges without this innovation become less attractive, lose market share of trading volume and thus experience a reduction in revenues from transaction fees. The holding companies of the extant exchanges suffer worsening operating and accounting performance, with reduced net income, earnings per share, and enterprise value. Investors punish their stock by ramping up short selling, creating negative cumulative abnormal returns. Given the rich academic literature on HFT that seeks to inform regulators on the merits and adverse effects of fast trading, our evidence from the counterfactual – the incorporation of an exchange with the new market design feature of a speed bump – should be useful as financial regulators worldwide debate the limits to speed competition.

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I. Introduction

Technological innovations in the securities exchange industry have facilitated high speed trading and created speed hierarchies (Hoffman, 2014). Traders with faster connections to access markets enjoy speed advantages over traders with slower connections, a situation that can lead to 'market exclusion' for slower traders, as modelled in Biais, Foucault, and Moinas (2015). While much academic research (Budish, Crampton, and Shim, 2015; Conrad, Wahal, and Xiang, 2015; Yao and Ye, 2018) examines how latency affects the market quality of the stocks on high speed platforms, there is scant evidence from the counterfactual of *throttled speed* via a speed bump. This paucity of evidence is primarily because until recently, there was no exchange that implemented an intentional delay. Faster speed was the only game in town.

Speed competition also affects order flow (Brolley and Malinova, 2013), thereby intensifying exchange competition and inducing changes in exchange operators' business models. Brolley and Cimon (2018) developed their theoretical propositions about the role of latency delay – known as speed bumps. Hu (2018) find that IEX has historically high market share, overall price discovery improves after its implementation of first lit speed bump. However, how innovation and the resulting changes in the speed of the market, market activities, competitive advantages redistribute market share, trading fees revenues, performance, returns, and the industrial organization of the exchange operators themselves is another area that has received less research focus. In this study, we contribute to the literature by addressing these gaps.

We conjecture that if a speed bump innovation is advantageous, it should improve the market quality of stocks and attract more order flow to the innovating exchange. Investors will reward the innovative exchange's holding company by increasing buying and reducing short selling of its stock. In contrast, competing exchanges without a similar innovation will lose market share of liquidity supply (National best bid and offer, i.e. NBBO quotes) and liquidity demand (trades) resulting in reduced transaction fees revenues. Transaction fees are now an important revenue source since traditional sources such as listing fees, membership fees, information services and market data have become less salient (Aggarwal, 2002). Falling behind on innovations in market design should lead to worse operating and accounting performance, as measured by balance sheet and income statement items including quarterly transaction fees revenues, quarter-over-quarter net income, earnings per share (EPS), and return on assets (ROA). Expectations of declining performance will be punished by investors with increased short selling of the non-innovating exchange operator's stock (Diamond and Verrechia, 1987; Dechow, Hutton, Meulbroek and Slown, 2001), creating negative cumulative abnormal returns (CARs) and reduced overall enterprise value (measured by Tobin's Q).

We test these conjectures using an exogenous event – the introduction of a new speed bump technology in the world of lit exchanges. Throttled speed or a speed bump is an intentional delay that can make an exchange more attractive to certain types of traders. In markets with high frequency traders (HFTs) who can undercut slower quotes, make trading outcomes unfavourable for traders with slower connections to access markets, and thereby drive them out, a speed bump can level the playing field and bring those traders back. By alleviating market exclusion, a speed bump may attract trading volume and transaction fees revenues away from venues without this innovation.

On June 17, 2016, the Securities and Exchange Commission (SEC) approved the Investors Exchange or IEX as a national securities exchange, introducing the first exchange with a speed bump in the world of lit exchanges in the US. IEX's intentional delay or speed bump technology uses a 38-mile optical fiber coil that sits in front of its matching engine and slows quotes and trades by about 350 microseconds.[1] Prior to its incorporation, IEX operated as a

1 See https://www.bloomberg.com/view/articles/2016-08-31/speed-bumps-are-the-hot-new-thing-for-exchanges

dark pool and reported its trades through FINRA. However, a dark pool with a speed bump is not expected to slow down fast traders in the lit markets because lit market orders are not obligated to be routed to dark venues and HFTs could detect order flow in certain stock exchanges and then undercut slow traders on other exchanges. Thus, the relevant exogenous event for our study is IEX's attainment of exchange status. Trading on IEX began with two stocks and by September 2, 2016, all listed U.S. stocks were trading on the IEX using the speed bump technology. After IEX gained exchange status, its speed bump could mitigate undercutting for traders whose orders are routed to IEX when it holds the NBBO, because both incoming and outgoing orders to and from IEX must go through its speed bump.

Following IEX's successful launch and quick increase in market share, some of the other established competing exchanges like Nasdaq Inc., the New York Stock Exchange and Chicago Stock Exchange all followed suit and petitioned the SEC with proposals for innovative speed bumps or new (resting) order types.[2] Yet notably, certain other exchanges owned by the CBOE continued to favor traditional high speed trading without any speed bump, allowing us to nicely segregate the exchanges into groups with or without the speed bump treatment.[3]

2 On November 17, 2016, Nasdaq petitioned to adopt an extended life priority order (ELO) attribute for retail orders that exist for a minimum of 1 second to receive higher priority, effectively creating a one-second resting time during which traders may not cancel orders. This petition was approved on July 7, 2017 (https://www.sec.gov/rules/sro/nasdaq/2017/34-81097.pdf). On January 27, 2017, NYSE MKT petitioned to create an access delay on its Pillar platform to add latency of 350 microseconds. This was approved on May 16, 2017 (https://www.sec.gov/rules/sro/nysemkt/2017/34-80700.pdf). On February 10, 2017, the Chicago Stock Exchange petitioned to adopt liquidity enhance access delay (LEAD), a speed bump with a 350-microsecond access delay to all orders except those submitted by LEAD market makers. This was approved but put on hold (10/25/2017) (https://www.sec.gov/rules/sro/chx/2017/34-81913.pdf; https://www.reuters.com/article/us-sec-chicagostockexchange/u-s-sec-puts-chicago-stock-exchange-speed-bump-on-hold-idUSKBN1CV3EC).

3 It is interesting to note that although there is intense competition among trading venues in the U.S., with 14 registered exchanges and 84 alternative trading systems (ATS), several of the exchanges are owned and operated by a smaller group of publicly listed holding companies. In particular, CBOE Global Markets Inc. (CBOE) operates and owns the National Stock Exchange (NSX), BATS EDGA Exchange Inc. (EDGA), BATS EDGX Exchange Inc. (EDGX), BATS BYX Exchange Inc. (BYX) and BATS BZX Exchange Inc. (BZX); the Intercontinental Exchange Inc. (ICE) operates and owns NYSE MKT LLC (NYSE MKT), New York Stock Exchange LLC (NYSE) and NYSE Arca Inc. (NYSE ARCA); Nasdaq Inc. (NDAQ) operates and owns Nasdaq OMX BX Inc. (Nasdaq BX), Nasdaq Stock Exchange LLC (Nasdaq) and Nasdaq OMX PSX Inc. (Nasdaq PSX).

We find that although the introduction of the lit speed bump via IEX's incorporation negatively impacted competing exchange operators' stock prices and performance in aggregate, this effect is strongest for the CBOE which had no actual or planned speed bumps, and not as much for the other operators who immediately petitioned to adopt this innovation. This differential impact helps isolate the effect of the new speed bump technology from the general competitive effects that would occur merely from an additional exchange entering the market. Comparing the quarters before and after IEX's incorporation, we find across the board reduction in average net income, transaction fees revenue, EPS, ROA, stock prices and the enterprise value of the competing exchanges as proxied by Tobin's Q. Disaggregated analyses show that these effects were most severe for the CBOE, which also experienced the largest increase in short selling of its own stock. Notably, CBOE operates the BATS exchanges, one of which was designed to offer particular advantages to low-latency traders according to many media mentions at that time.[4]

We present in-depth order flow and market quality analysis for stocks trading on various exchanges to verify that the speed bump is indeed the cause of the changing market share of exchange operators. As a stark (albeit anecdotal) example of changing market shares, the National Stock Exchange (NSX) owned and operated by the CBOE ceased trading operations on February 1, 2017. CBOE lost significant ground as measured by share volume and the number of trades. In the meanwhile, IEX increased its market share to 2.85% within a few months of operations. Interestingly, ICE and Nasdaq did not suffer as badly; they were quicker to prepare themselves to adopt some form of speed bump technology in the near future. CBOE has not filed any request to adopt or launch any latency-delay innovation at the time of this writing (June 2018). CBOE's losses likely came from IEX's direct impact on the business model of its BATS exchanges. As alluded to before, industry observers opined that the BATS

[4] See https://www.nytimes.com/2014/04/06/magazine/flash-boys-michael-lewis.html

platforms that facilitate order detection strategies would be the hardest hit by IEX's speed-bump, a prediction that finds confirmation in our data as we probe this issue further and examine changes to informed trading following the lit speed bump implementation.

HFTs enjoy a speed advantage over traders who uncover fundamental information (Haldane, 2011). If HFTs observe their order flow and undercut these fundamental value traders, this will increase their trading cost and reduce their trading intensity (Li, 2014). Since the lit speed bump's speed levelling was intended to discourage such undercutting strategies, we expect order flow to carry greater information post implementation. In alignment with our expectations we find that price discovery, as proxied by the odd lot rate (O'Hara, Yao and Ye, 2014), increased. Brolley and Cimon (2018) propose that the net effect of an exchange that introduces a latency delay in the fragmented market is an increase in total exchange traded volume and informed order flow migrates to the standard exchanges. Consistent with their proposition, we find that both number of orders and number of trades on exchanges increased and that the delayed exchange has the lowest informed trading. Moreover, we find decreases in quoted spread, quote-to-trade ratio, cancel-to-trade ratio, order imbalance, proportion of flickering quotes, cancellation speed, fill speed, NBBO revision speed and trading speed, and increased quoted depth suggesting that market quality improved after the lit speed bump implementation.

Diving deeper into the analysis of order flow that relies on speed advantage, and can be mitigated with a speed bump, we also run additional first-order autoregression tests in a multimarket context. These tests gauge whether trades executed on different exchanges show signs of follow-on trading strategy, and if the introduction of IEX's speed-bump had any effect on such trends. These tests are motivated by the literature that model high speed trader behavior as front-running and back-running (Yang and Zhu, 2016) to undercut slower traders. We find that the exchanges operated by the CBOE experience a reduction in follow-on order strategy proxied by the autocorrelation of trade directions (Holden and Jacobsen, 2014). Thus, the speed bump technology appears to be the main driver for the changes in attractiveness of various exchanges as trading platforms of choice. Given the rich academic literature on HFT that seeks to inform regulators on the merits and adverse effects of fast trading, our evidence from the counterfactual – the incorporation of an exchange with a speed bump – should be useful as financial regulators worldwide debate the limits to speed competition.

The remainder of the paper is organized as follows. Section II provides the background for speed bump technology and IEX. Section III describes the data and sample selection. Section IV presents and discusses variable construction, research design and empirical results and Section V concludes.

II. HFT Speed and speed bump in the lit markets

In this section, we provide a brief background on the problems arising from the speed advantage of some HFTs that led to the speed bump innovation as a mitigating feature. The key problem for slightly slower traders with traditional connections to access exchanges was identified by Brad Katsuyama, a former Royal Bank of Canada trader. He found that when he sent orders to multiple exchanges, only the orders sent to BATS got 100% execution, while orders routed to the other exchanges had lower execution rates due to swifter counterparty limit order cancellations. Upon further examination, his team concluded that a possible explanation was that the BATS exchange, which had been created by HFT firms, was always the first stock exchange to receive orders due to the complicated layout of the fiber-optic network. It allowed HFTs to deploy order detection strategies and then undercut these orders on other exchanges. They did this by cancelling their standing limit orders once they detected an incoming marketable order and placing new orders at slightly inferior prices. Though the price differential between the cancelled and newly placed orders was typically less than 0.1% of the total price, this practice would cost traders about $160 million a day in the U.S. market (Lewis, 2014). Katsuyama could see orders at the various exchanges when placing his order, but by the time his orders reached the exchanges, the (displayed) liquidity had vanished everywhere else except BATS. Clearly, such strategies could only be deployed when traders have heterogeneous speeds at which they can access markets.

Katsuyama had the idea to counter what he perceived to be unfair speed competition by creating a new trading venue called the Investors Exchange. IEX imposed a speed bump of 350 microseconds on orders through its 38-mile fiber-optic coil which prevented the fastest traders to undercut other orders when parts of the customers' orders are executed on IEX. IEX began as a dark pool on October 25, 2013. When it was approved as a stock exchange on June 17, 2016, the SEC issued an updated interpretation that requires trading centers to honor stock prices that were subject to a speed bump (in effect reinterpreting sections of the Reg NMS rule that requires quote data to be disseminated as quickly as possible). Thus, into the landscape of speed competition among exchanges entered IEX, a stock exchange that deterred speed competition with intentional latency increase.

Trading on the IEX began on August 19, 2016 with two stocks –Vonage (VG) and Windstream Holdings (WIN). Another eight stocks were introduced on August 24, 2016. Then all stocks whose tickers start with the letters "Y" and "Z" started trading on IEX on August 29, 2016. Finally, all remaining stocks were brought on to the IEX platform on September 2, 2016. As reported by IEX, its market share (calculated as IEX traded volume divided by total market volume) increased from 1.42% on August 2016 to 2.22% in August 2017 and to its peak at 2.85% on November 2017. IEX's average market share in April 2018 was 2.34%.[5]

[5] https://iextrading.com/stats/#historical-stats

The particular speed bump mechanism IEX uses applies a unique intentional delay including Point-of-Presence (POP) and coil infrastructure (POP/coil delay). From his days as a trader, Katsuyama estimated that the necessary delay to neutralize HFT firms' undercutting advantage was about 320 microseconds, so he rounded the intentional delay up to 350 microseconds (Lewis, 2014). This delay applies to all users equally and cannot be bypassed by paying a fee or otherwise (SEC, 2016). In order to access IEX, all users must send electronic messages to IEX's POP in the Equinix data center in Secaucus, NJ, physically traversing the 38-mile coil of fiber-optic cable in a box and then an additional physical distance to IEX's trading system in Weehawken, NJ. The total transmission time creates an intentional latency of 350 microseconds (SEC, 2016). Figure 1 depicts how IEX's speed bump (POP/coil deilay) works.

[Figure 1 here]

All incoming messages (buy/sell orders, modification to existing open orders) and outbound messages (order execution confirmation) must traverse the POP and the coil before reaching IEX's trading system (inbound) or the user (outbound). IEX's direct proprietary market data feed also goes via the speed bump. To avoid affecting IEX's ability to detect and react to price changes on other trading centers, IEX allows inbound proprietary market data feeds from other trading centers and SIP, and outbound messages to other trading centers and SIP, to bypass the speed bump (SEC, 2016).

III. Data and sample selection

Our sample period ranges from Q1 2012 to Q2 2017 covering both the lit speed bump implementation (IEX's incorporation in Q3 2016) which is our main event of interest, and dark pool speed bump (IEX's introduction in Q4 2013). Our data come from several sources. To test for any changes in the performance of extant exchange operators (CBOE, ICE and NDAQ), we collect their quarterly net income, transaction fees revenue, EPS, total assets, number of shares outstanding, total liabilities, operating cash flow, revenue and stock price on the last day of each quarter from Bloomberg. To create appropriate benchmarks against which to compare these exchange operators' performance we also collect analogous information for the constituents of S&P Financials and S&P 500 from Bloomberg. We obtain short interest data for the exchange operators' own stocks as well as the benchmark stocks from Compustat.

[Table 1 here]

In Table 1 Panel A, we report the descriptive statistics for the average performance of exchange operators and their own stocks for the overall sample periods from Q1 2012 to Q2 2017. This is primary data for the direct assessment of the impact of speed bump technology on exchange operators themselves.

In Table 1 Panel B, we report the descriptive statistics of the representative sample of firms that are traded on the exchanges. This sample is used later on in the paper to assess the liquidity services provided by the exchange operators for the traded firms. Analysis of this indirect performance mechanism is necessary because exchange operators own performance is dependent on their relative attractiveness before and after the speed bump in providing liquidity services. The average market capitalization for the traded firms for which exchanges provide liquidity services is $1,504 million. We break down the statistics based on market capitalization of the listed firms and find that larger firms tend to have higher average trading volume and lower returns. We also present conditional statistics based on listing exchange of the sample firms.

To analyse the impact of the speed bump on informed order strategies, quote and trade activity, market quality and market shares of exchanges, we obtain millisecond level intra-day trade and quote data from the NYSE DTAQ database. We follow Holden & Jacobsen (2014) to interleave the NBBO and quote files to obtain the NBBO. We follow Lee and Ready (1991) to classify trade direction, but adapt their algorithm's logic to modern day improved clock synchronization by lagging quotes only by one millisecond to match quotes with trades. We delete trade records with missing or zero price or volumes, and quote records with missing or zero price or volumes or bid greater than ask. For speed related metrics, we use nanosecond level order data from Nasdaq's ITCH database that provides all message traffic arriving at Nasdaq's trading platform. The dataset has order submission, execution, cancellation and modification records, each of which has a reference number, price, size and buy/sell indicator. For market-wide cancel to trade and odd lot rates, we use SEC Market Structure (MIDAS) data. Finally, we obtain the daily number of quotes and trade for IEX before it appears in DTAQ directly from that exchange upon request.

For our tests on market quality and informed trading, we consider a 10-day window (5 pre- and 5-post) centered on the date IEX began trading as an incorporated exchange. We collect daily data including stock price, number of shares outstanding, trading volume and share code from CRSP. We select a representative sample of stocks by following Chakravarty, Jain, Upson & Wood (2012). The sample is chosen based on the listed firms' market capitalization on August 24, 2016 and the following criteria: The stocks must exist at the intersection of the DTAQ and CRSP databases, have closing price greater than $10 and less than $1000 on August 24, 2016, and must be a common stock with CRSP share code 10 or 11. All stocks that meet these criteria are grouped as small, medium or large based on market capitalization. The top 50 stocks, based on market capitalization, from each group form the sample of 150 stocks included in this study.

IV. Variable construction, research design and empirical results

A. Speed of reaction to order book events

We first examine order reaction, cancellation, fill, NBBO revision and trading patterns on Nasdaq to gauge the latency-related effects of the introduction of the POP/coil delay. An intentional speed bump delay can decrease the speed of HFTs and make it difficult to engage in order detection and potentially undercut (Lewis, 2014) and back-run (Yang and Zhu, 2016) the detected orders. This can facilitate increased reaction times and quote life. We utilize ITCH data to examine if such changes occurred.

We measure order cancellation and fill pattern based on reaction speed, cancellation speed and fill speed using timestamps in the ITCH data. Following Chakrabarty, Jain, Shkilko and Sokolov (2018), we measure the reaction speed as the difference between the time it takes Nasdaq liquidity providers to cancel or revise their limit order after an order is executed on a remote market. Cancellation speed is the difference between the time a limit order on Nasdaq is added and the time the same order is cancelled or revised on Nasdaq. Fill speed is the difference between the time a limit order on Nasdaq is added and the time the same order is executed on Nasdaq. For these speed measures, we create the following time buckets: 1 ms (millisecond), 2 ms, 3 ms, 4 ms, 5 ms, 10 ms, 100 ms and 100+ ms and then calculate the proportion of orders that fall into each bucket. The 1 ms time bucket contains all reaction/cancellation/fill that occur within the first millisecond, the 2 ms bucket contains those occurring between the first and the second milliseconds, and so on. We also measure NBBO revision speed, trading speed after an NBBO revision and NBBO revision speed after a trade using DTAQ data. We measure the NBBO revision speed as the difference between the time an NBBO is posted and the subsequent NBBO update. Trading speed after NBBO is measured as the difference between the time an NBBO is posted and the time a trade is executed subsequently. Post trade NBBO revision speed is measured as the difference between the time a trade is executed and the time a new NBBO is posted subsequently.

We test for changes in the speed of order book reaction, cancellation, fill, NBBO revision, and trading before and after NBBO updates pre- and post-lit speed bump implementation, by estimating the following two models:

$$Speed\ bucket\ proportion_{i,t} = \beta_0 + \beta_1 Lit\ speed\ bump_t + \delta_1 Iprice_{i,t} + \delta_2 Mcap_{i,t} + \varepsilon_{i,t} \qquad (1)$$

$$Speed\ bucket\ proportion_{i,t} = \beta_0 + \beta_2 Lit\ speed\ bump_t + \delta_1 Iprice_{i,t} + \delta_2 Mcap_{i,t} + \delta_3 Volt_{i,t} + \delta_4 Turn_{i,t} + \varepsilon_{i,t} \qquad (2)$$

where $speed\ bucket\ proportion_{i,t}$ is one of the variables for stock i on day t as defined before. Lit speed bump_t is a dummy variable equals 1 in post-lit speed bump implementation period (September 6, 7, 8, 9, 12, 2016), 0 otherwise; $Iprice_{i,t}$ is the inverse of the stock price for stock i on day t; $Mcap_{i,t}$ is market capitalization for stock *i* at day *t*, $VOLT_{i,t}$ is volatility for stock *i* on day *t*, and $TURN_{i,t}$ is turnover for stock *i* on day *t*. The regressions are estimated with stock fixed effect and serve to examine the proposed hypothesis that speed changes after lit speed bump implementation.

[Table 2 here]

Table 2 presents the speed of liquidity providers' reactions in different time buckets. In Table 2 Panel A, we examine the reaction (i.e. cancellations and revisions) on Nasdaq that happens after a trade is executed on a remote market. We find that such reactions generally tend to cluster in the first time bucket (less than 1 ms) and the last time bucket (orders cancelled/revised in more than 100 ms) which account for 45.0% and 27.4% of total cancellation and revisions, respectively. Table 2 Panel B shows that orders in the first time bucket decreased after the lit speed bump implementation. The proportion of order cancellation and revision increased in other time buckets. The OLS regression results in Table 2 Panel C imply a stronger impact of the lit speed bump. The coefficients of lit speed bump dummy are negative for flickering orders in both models while those of lit speed bump dummy are positive for orders in time buckets of slower reaction speed. These findings suggest that IEX's speed bump has the hypothesized impact. Lower proportion of orders on Nasdaq are cancelled or revised after a trade is executed on a remote market within 1 ms. These results signify that the type of undercutting concerns raised by Lewis (2014) and back-runners' behaviour in period 1 modelled in Yang and Zhu (2016) are potentially mitigated by the POP/coil delay and results in improved market quality.

[Figure 2 here]

Figure 2 depicts that the 1 ms and 100+ ms time bucket have the largest and second largest proportion of the reaction. The proportion of 1 ms time bucket decreased while the proportions of longer time buckets increased post-lit speed bump implementation, suggest that reaction times to order flow increased.

[Table 3 here]

We also examine whether quote life is extended after IEX's incorporation. Table 3 presents cancellation speed in different time buckets. In Table 3 Panel A, we find that 73% of order cancellations and revisions on Nasdaq happens after 100 ms since the order was added. Table 3 Panel B reports that the proportion of cancellation and revision within 1 ms decreased by 6% after the lit speed bump implementation. The proportion in the 100 ms and 100+ ms time buckets also decreased though not statistically significantly. The OLS regression results in Table 3 Panel C show stronger impact. The coefficients of lit speed bump dummy are negative for 1 ms, 100 ms and 100+ ms time buckets in both models while those of lit speed bump dummy are positive for orders in time buckets between them. The decreased proportion in 1 ms time buckets is greater than the combined decreased proportion of 100 ms and 100+ ms suggesting that cancellation speed decreased in aggregate. This is also consistent with the hypothesized impact of a POP/coil delay.

[Table 4 here]

Table 4 presents fill speed in different time buckets. In Table 4 Panel A, we find that 84.4% of orders on Nasdaq are filled after 100 ms since the order was added. Table 4 Panel B reports that the proportion of filled orders within 1 ms, 2 ms and 3 ms decreased by 3%, 14% and 10% respectively after the lit speed bump implementation. The proportion in the longer time buckets increased. The OLS regression results in Table 4 Panel C show consistent impact. The coefficients of lit speed bump dummy are negative for 1 ms, 2 ms and 3 ms time buckets in both models while those of the lit speed bump dummy are positive for orders in longer time buckets. This is also consistent with the hypothesized impact of POP/coil delay. Taken together the results in Tables 11 and 12 suggest that orders have longer life after the lit speed bump implementation.

[Table 5 here]

Table 5 presents NBBO revision speeds in the different time buckets. In Table 5 Panel A, we find that such revisions generally tend to cluster in the first time bucket (less than 1 ms) and the last time bucket (more than 100 ms) each of which accounts for 49.7% and 27.2% of total NBBO revision. Table 5 Panel B reports that the proportion of NBBO revision within 1 ms decreased by 5% after lit speed bump implementation. The proportion in the 100+ ms time bucket also decreased slightly by 3%. The OLS regression results in Table 5 Panel C show consistent impact. The coefficients of lit speed bump dummy are negative for 1 ms and 100+ ms time buckets in both models while those of lit speed bump dummy are positive for NBBO revision in time buckets between them. Overall, NBBO revision speed decreased which is consistent with the hypothesized impact of the POP/coil delay.

[Table 6 here]

Table 6 presents trading speed after NBBO revision in different time buckets. In Table 6 Panel A, we find that trading after NBBO revision generally tend to cluster in the first time bucket (less than 1 ms) and the last time bucket (more than 100 ms) which accounts for 57.4% and 26.3% of total trading after NBBO revision, respectively. Table 6 Panel B reports that the proportion of trading after NBBO revision within 1 ms decreased by 1% after lit speed bump implementation. The proportion in 10 ms time bucket also slightly decreased. The OLS regression results in Table 6 Panel C show consistent impact. The coefficients of lit speed bump dummy are negative for 1 ms and 10 ms time buckets in both models while those of lit speed bump dummy are positive for trading NBBO revision in other time buckets.

[Table 7 here]

Table 7 presents NBBO revision speed after trading in different time buckets. As before, NBBO revision after trading tend to cluster in the first and last time buckets in Table 7 Panel A. Table 7 Panel B reports that the proportion of trading after NBBO revision within 1 ms decreased by 1% after the lit speed bump implementation. The proportion in the 100+ ms time bucket also slightly decreased. The OLS regression results in Table 7 Panel C show that the coefficients of lit speed bump dummy are negative for 1 ms and 100+ ms time buckets in both models while those of lit speed bump dummy are positive for NBBO revision in time buckets between them, consistent with the hypothesized impact of POP/coil delay. The results in Tables 12, 13 and 14 suggest that NBBO revision, trading after NBBO revision and NBBO revision after trading take longer time after lit speed bump implementation, consistent with the delay reducing the fastest reaction times.

B. Market quality and informed trading metrics

While IEX's speed bump technology was a competitive threat to extant exchange operators (and CBOE indeed experienced negative effects), it is a separate question how the same technology affected the market quality of stocks trading on these platforms. Thus, we next examine whether the lit speed bump benefitted investors by improving market quality.

The literature offers no consensus expectation in this regard. Some studies show that fast traders may act as both liquidity demanders as well as liquidity suppliers (Brogaard, Hagströmer, Nordén and Riordan, 2015; O'Hara, 2015; Baron, Brogaard, Hagströmer and Kirilenko, 2017). Others, for example, Foucault, Kozhan, and Tham (2017) offer a model where reducing the numbers of latency-sensitive traders allows others to efficiently reprice their orders and thereby improve market quality. We expect that trading cost due to adverse selection will decrease post-lit speed bump implementation if the speed advantage of previous fast traders who exploit slow traders is negated (Biais et al., 2015).

Jarnecic and Snape (2014) find that HFT's fast order cancellation makes trading more difficult and costly for long-term investors who do not possess fast-trading technology, which reduces market depth. We then expect market depth to increase post lit speed bump implementation. According to Hasbrouck and Saar (2009 & 2013), order cancellation increases with trading speed. With lit speed bump to slow down speed, we expect order cancellations to decrease. O'Hara et al. (2014) propose that informed traders tend to split their orders into odd-lot to hide their information. We expect odd lot trades to increase if undercutting is mitigated by the POP/coil delay.

We measure market quality using 4 metrics – quoted spread, best bid/ask depth, cancel to trade ratio and order imbalance. We measure informed trading using 2 metrics – odd lot rate and ISO rate. Following Holden & Jacobsen (2014), we define quoted spread as the time-weighted NBBO spread which is:

$$Time-weighted\ Quoted\ Spread = (National\ Best\ Ask_t - National\ Best\ Bid_t) * Time\ weight \tag{3}$$

Dollar quoted spread is the time-weighted average of dollar quoted spread computed over all time intervals between NBBO updates. Time weight is the number of seconds a quote is in force divided by the total number of seconds in the day.

We define time-weighted dollar best ask depth as the product of best ask price and best ask size multiplied by time weight. Similarly, we define time-weighted dollar best bid depth as the product of best bid price and best bid size multiplied by time weight.

$$Time - weighted\ Dollar\ Best\ Ask\ Depth = Best\ ask\ price * \ Best\ ask\ size * Time\ weight \quad (4)$$

$$Time - weighted\ Dollar\ Best\ Bid\ Depth = Best\ bid\ price * \ Best\ bid\ size * Time\ weight \quad (5)$$

We define cancel to trade ratio as the ratio of number of cancels and the number of lit trades (difference between the number of total trades and number of hidden trades).

$$Cancel\ to\ Trade = \frac{Number\ of\ cancels}{Number\ of\ total\ trades - Number\ of\ hidden\ trades} \quad (6)$$

We define order imbalance as absolute value of the ratio between the difference between the number of buy orders and the number of sell orders, and the sum of the number of buy orders and the number of sell orders.

$$Order\ Imbalance = \left| \frac{Number\ of\ buy\ orders - Number\ of\ sell\ orders}{Number\ of\ buy\ orders + Number\ of\ sell\ orders} \right| \quad (7)$$

We define odd lot rate as the ratio of the number of odd lot trade and the number of trades from order-based exchanges, multiplied by 100.

$$Odd\ Lot\ Rate = \frac{Number\ of\ odd\ lot\ trades}{Number\ of\ trades} * 100 \quad (8)$$

We define intermarket sweep order (ISO) rate as the ratio between number of ISO orders and the number of trades.

$$ISO\ rate = \frac{Number\ of\ ISO}{Number\ of\ total\ trades} \tag{9}$$

To examine changes in market quality and informed trading following the lit speed bump implementation, we test the difference between the mean of these metrics post- and pre-lit speed bump implementation following Hendershott, Jones & Menkveld (2011) and estimating the following two models:

$$Market\ quality\ or\ informed\ trading_{i,t} = \beta_0 + \beta_1 Lit\ speed\ bump_t + \delta_1 Iprice_{i,t} + \delta_2 Mcap_{i,t} + \varepsilon_{i,t} \tag{10}$$

$$Market\ quality\ or\ informed\ trading_{i,t} = \beta_0 + \beta_2 Lit\ speed\ bump_t + \delta_1 Iprice_{i,t} + \delta_2 Mcap_{i,t} + \delta_3 Volt_{i,t} + \delta_4 Turn_{i,t} + \varepsilon_{i,t} \tag{11}$$

where $Market\ quality\ or\ informed\ trading_{i,t}$ is one of the 7 variables for stock i on day *t*; $Lit\ speed\ bump\ _t$is a dummy variable that equals 1 in post-lit speed bump implementation period (September 6, 7, 8, 9, 12, 2016), 0 otherwise; Same set of control variables are included as previously defined for model (1) and (2). The regressions are estimated with stock fixed effect and serve to examine the proposed hypothesis that market quality improved after lit speed bump implementation.

[Table 8 here]

In Table 8 Panel A, we report summary statistics and lit speed bump-related changes in market quality and informed trading metrics. In Table 8 Panel B, we find that best bid depth and best ask depth both increased significantly by 78% and 68% respectively. Order imbalance decreased and odd lot rate increased post-lit speed bump implementation by 12% and 13% respectively. The OLS regression results in Table 8 Panel C show stronger impact. The coefficients of lit speed bump dummy are negative for quoted spread, cancel to trade ratio and order imbalance in either both regression models, or one of the two models. The coefficients of lit speed bump dummy are positive for best bid depth, best ask depth and odd lot rate. These results are consistent with the literature and expected results. Market quality indeed improved and informed trading increased as a result post-implementation.

We also compute odd lot rate as a proxy of informed trading for exchanges and their operators to empirically test Brolley and Cimon (2018)'s proposition 1 that informed traders send more orders to standard (i.e. fast) exchanges. Table 9 reports the results.

[Table 9 here]

Table 9 shows that informed trading on all the operators of standard exchanges increased. In particular, informed trading on CBOE increased significantly by 1.86%. Informed trading on ICE and NDAQ also increased by 1.34% and 0.53% though not statistically significantly. These findings are consistent to Brolley and Cimon (2018). After the lit speed bump implementation, IEX, the delayed exchange has the lowest odd lot rate (7.82%) among all exchanges that is also consistent to proposition 1 of Brolley and Cimon (2018).

C. Follow-on strategy

We run first-order autoregressions to test whether trades executed on different exchanges show signs of follow-on trading strategy, and if the introduction of POP/coil delay had any effect on such trends. Table 10 presents the summary of the follow-on order strategy results.

[Table 10 here]

We find that the parameter estimates for all the CBOE owned stock exchanges (BYX, BZX, EDGA, EDGX and NSX) decreased after the POP/coil delay was implemented and they are all statistically significant, lending some credence to the anecdotal claims that CBOE's BATS exchanges facilitated HFT strategies, and the POP/coil delay reduced the scope to implement such strategies. Among the 3 exchanges operated by ICE, we find that the parameters of NYSE and NYSE Arca decreased while NYSE MKT increased. Among the 4 exchanges operated by NDAQ, we find that the parameters of Nasdaq BX, Nasdaq Tape AB and Nasdaq PSX decreased while Nasdaq Tape C increased. The parameters of CHX and FINRA both increased but FINRA's is not statistically significant. Notably, the parameter of IEX is negative.

D. Market activity, systemic risk and market share

In this section, we examine whether speed bump will increase market activity in lit market as predicted by Brolley and Cimon (2018), which in turn can affect the division of market share of trading volume among exchange operators. Our measures of market activity are log-transformed number of quotes and number of trades. We also divide the number of quotes by number of trades to obtain quote-to-trade ratio to measure quote stuffing risk, a type of systemic risk. We measure market share based on volume and number of trades for each of the exchanges and their operators. We divide volume and number of trades for each exchange (operator) by total volume and total number of trades, respectively, for the whole market to calculate trade market shares. Similar method is adopted to calculate NBBO market shares.

To examine changes in quote and trade activity and quote stuffing risk post-lit speed bump implementation, we test the difference between the means of each metric pre- and post-lit speed bump implementation by estimating the following two models:

$$Quote\ or\ trade\ activity_{i,t} = \beta_0 + \beta_1 Lit\ speed\ bump_t + \delta_1 Iprice_{i,t} + \delta_2 Mcap_{i,t} + \varepsilon_{i,t} \quad (12)$$

$$Quote\ or\ trade\ activity_{i,t} = \beta_0 + \beta_2 Lit\ speed\ bump_t + \delta_1 Iprice_{i,t} + \delta_2 Mcap_{i,t} + \delta_3 Volt_{i,t} + \delta_4 Turn_{i,t} + \varepsilon_{i,t} \quad (13)$$

where $Quote\ or\ trade\ activity_{i,t}$ is one of the following variables for operator i on day t in separate regressions: quotes, defined as log-transformed number of quotes; trades, defined as log-transformed number of trades; and QTR, defined as log-transformed number of quotes divided by log-transformed number of trades. $Lit\ speed\ bump_t$ is a dummy variable that equals 1 in post-lit speed bump implementation period (September 6, 7, 8, 9, 12, 2016), 0 otherwise; Same set of control variables are included as previously defined for model (1) and (2). The regressions are estimated with stock fixed effect and serve to examine the proposed hypothesis that market activity improved after the lit speed bump implementation.

[Figure 3 here]

Figure 3 shows that IEX's number of daily quotes, number of daily trades, market share and trading volume on IEX matching engine increased post-lit speed bump implementation, suggesting that traders perceive speed bump as a beneficial innovation.

[Table 11 here]

Table 11 shows that the quote to trade ratio decreased by 7% although both number of daily quotes and number of daily trades increased by 4% and 5% respectively post-lit speed bump implementation. The finding is consistent to the prediction that the net effect of latency delay is an increase in total exchange-traded volume. Given that one way the quote to trade ratio increases is from HFTs splitting orders and submitting a large number of orders and subsequently cancelling most (Hasbrouck and Saar, 2013; Conrad et al., 2015 and O'Hara, 2015), a decreased quote to trade ratio suggests a reduction in this type of HFT activities that creates uncertainty about NBBO and liquidity. Consistent with the finding that lower latency generates higher quote stuffing risk (Eggington, Van Ness and Van Ness, 2016; Jain, Jain and McInish, 2016), slower trading speed caused by lit speed bump reduces quote stuffing risk.

We also compute market share using the average of volume and number of trades on the 5 trading days (September 6, 7, 8, 9, 12, 2016) just after IEX began trading all stocks and 5 trading days (August 25, 28, 29, 30, 31, 2017) after the speed bump application of ICE and NDAQ were approved by the SEC on May 16, 2017 and July 7, 2017 respectively, that is about one year after IEX became a stock exchange. Table 12 reports the results.

[Table 12 here]

It shows that CBOE (whose BATS exchanges is popular among HFTs) lost market share in terms of volume (-4.90%) and number of trades (-2.63%) in Table 12 Panel A and B. The change in market share volume for ICE and NDAQ are not statistically significant, though they are positive (2.88% and 2.82% respectively). Except ICE's market share of the number of trades, both ICE and NDAQ's market shares based on volume and number of trades increased post-lit speed bump. NSX (owned by CBOE) ceased trading operations on February 1, 2017. IEX itself gained market shares in terms of volume and number of trades and its gains are sharper than extant exchange operators.' In Table 12 Panels C and D, we find that immediately after the lit speed bump implementation, CBOE lost market share in the national best bid (NBB) and national best offer (NBO) quotes, by 2.88% and 2.90% respectively.

E. Operators' performance and investors' reaction to lit speed bump

We measure exchange operator performance before and after lit speed bump using 5 metrics –net income, transaction fees revenue, EPS, ROA, and Tobin's Q. ROA is net income divided by total assets, and Tobin's Q is the market value of common shares divided by total assets. To isolate the impact of the speed bump from other market-wide factors, we normalize these performance metrics by subtracting analogous measures for the S&P Financials and/or the S&P 500 Indices. Likewise, we calculate abnormal returns by subtracting the S&P Financials and/or S&P 500 from daily stock return of the exchange operator. CARs are calculated in 3 event windows: (-1, +1), (-2, +2) and (-3, +3) around the announcement date of SEC's approval of IEX's exchange status. Transaction fees revenue is defined as total transaction fees divided by total revenue. Transaction market share is transaction fees divided by the sum of transaction fees of CBOE, ICE and NDAQ. Short interest is the average of short position in the quarter.

[Table 13 here]

We first investigate the cause of the negative impact on competing exchanges with no actual or planned speed bump by looking at the changes in transaction fees, which is the most important source of revenue for stock exchanges (Aggarwal, 2002).

$$Operators' transaction\ fees\ revenue_{i,t} = \beta_0 + \beta_1 Lit\ speed\ bump_t + \sum_i^{\delta}\left(control\ variables_{i,t}\right) + \varepsilon_{i,t} \quad (14)$$

$$Operators' transaction\ fees\ revenue_{i,t} = \beta_0 + \beta_1 Lit\ speed\ bump_t + \beta_2 Dark\ speed\ bump_t + \sum_i^{\delta}(control\ variables_{i,t}) + \varepsilon_{i,t} \quad (15)$$

where $Operators'\ transaction\ fees\ revenue_{i,t}$ is transaction fees revenue or transaction fees market share for operator i in quarter t; $Lit\ speed\ bump\ _t$ is a dummy variable equal to 1 in post-lit speed bump implementation period (Q4 2016 to Q2 2017), else 0; $Dark\ speed\ bump_t$ is a dummy variable that equals 1 in post-dark pool speed bump implementation period (Q1 2014 to Q2 2017), else 0; Control variables are the following variables in quarter t-1: *Leverage*, defined as total liabilities divided by total assets; *Size*, defined as log of total assets; *Asset turnover*, defined as revenue divided by total assets; *Operating cash flow*, defined as operating cash flow divided by total assets. The regressions are estimated with stock fixed effect.

We regress transaction fees revenue on lit speed bump dummy and the same set of controls, from Q1 2012 to Q2 2017. Table 13 Panel A shows that exchanges with no actual or planned speed bump owned by CBOE experience a significant decline in transaction fees revenue. But ICE and NDAQ immediately announced plans to adopt speed bumps in near future and did not suffer from declining transaction fees revenue as shown in Panels B and C of Table 13. Panels D, E and F show that CBOE loses market share to ICE and NDAQ in terms of transaction fees.

Taken together, these results indicate that the speed bump has an impact that is different from the general effects of competition from a new entrant.

To examine the impact of lit speed bump implementation on extant exchange operators, we estimate the following regression models:

$$Operators'performance_{i,t} = \beta_0 + \beta_1 Lit\ speed\ bump_t + \textstyle\sum_i^{\delta}\left(control\ variables_{i,t}\right) + \varepsilon_{i,t} \quad (16)$$

$$Operators'\ performance_{i,t} = \beta_0 + \beta_1 Lit\ speed\ bump_t + \beta_2 Dark\ speed\ bump_t + \textstyle\sum_i^{\delta}(control\ variables_{i,t}) + \varepsilon_{i,t} \quad (17)$$

where $Operator\ performance_{i,t}$ is one of the following variables for operator *i* in quarter *t*: net income, EPS, ROA and Tobin's Q; $Lit\ speed\ bump\ _t$ is a dummy variable equal to 1 in post-lit speed bump implementation period (Q4 2016 to Q2 2017), else 0; $Dark\ speed\ bump_t$ is a dummy variable that equals 1 in post-dark pool speed bump implementation period (Q1 2014 to Q2 2017), else 0; Control variables are the same as those in equation (14) and (15).

[Table 14 here]

Table 14 Panel A shows that all performance metrics also dropped after the lit speed bump implementation for competing exchanges in aggregate. On average, extant exchange operators' ROA and Tobin's Q dropped sharply by 14% and 21%, respectively, from Q1 2016 to Q1 2017. Net Income, EPS and transaction fees revenue dropped by 2%, 3% and 8%, respectively. When examining each exchange operator separately, the drop is mainly attributable to CBOE whose ROA, Tobin's Q, Net Income, EPS and transaction fees revenue decreased by 98%, 87%, 69%, 73% and 21%, respectively. In contrast to decreased short interest of ICE and NDAQ, short interest of CBOE increased by 22%. These findings suggest that the implementation of IEX's lit speed bump has the most adverse impact on CBOE which had no actual or planned speed bump adoption on the horizon. This result dovetails nicely with the prevalent notion that IEX's technology was a direct rebuttal to CBOE's business model for the BATS exchanges (Lewis, 2014) which lost out on order flow, a conjecture we test in analysis presented later.

To provide a benchmark for comparison, we calculate the same set of metrics (except transaction fees revenue because non-exchange operators do not have this) for S&P Financials and S&P 500 by taking the mean of each of the metrics of their respective constituents. Table 14 Panel B confirms that the ROA, Tobin's Q, Net Income and EPS of CBOE declines and short interest increases after adjusting for the trends in S&P Financials and S&P 500 over the same time period. After adjusting for these same benchmarks, the two other exchange operators, ICE and NDAQ, that adopted their own versions of speed bumps later on, are not adversely affected by IEX's speed bump. We caution, however, that the above results come from univariate analyses. Thus, while they may be indicative, they do not control for other factors that may impact these results. Using panel data from Q1 2012 to Q2 2017, we next conduct OLS regressions that control for leverage, size, asset turnover and operating cash and report results in Table 15.

[Table 15 here]

These regression results confirm the findings in Table 14. Table 15 Panel A shows that the incorporation of the lit speed bump has a negative and significant impact on S&P Financials adjusted performance metrics in model 1 and model 2 except Tobin's Q. In these regressions we control for the event when IEX became operational as a dark pool. The insignificant coefficients on *Dark speed bump* indicate that it is the introduction of the speed bump in the lit market, and not the speed bump technology operating in a dark pool, that has this effect. We also regress each operator's performance metrics on lit speed bump and the same set of control variables. Table 15 Panel B reports that the lit speed bump has negative and statistically significant impact on CBOE's S&P Financials adjusted ROA, Tobin's Q, Net Income and EPS.

Table 15 Panels C and D show that the lit speed bump has no significant impact on ICE and NDAQ. These findings confirm that the lit speed bump adversely affects CBOE by negating the speed advantage of faster traders.

[Table 16 here]

If the introduction of the lit speed bump adversely affects extant exchange operators, we should expect negative reaction around the (SEC approval) announcement date, which is the event date or day 0. Table 16 shows that individual CARs of the exchange operators (ranging from -1.13% to -4.40%) as well as overall CARs (ranging from -2.14% to -4.32%) using both S&P Financials and S&P 500 as the benchmark in the (-1,+1), (-2,+2) and (-3,+3) windows are indeed all negative and statistically significant, suggesting that investors perceive this technology as a competitive threat to the extant exchange operators. Each of the 3 exchange operators experienced negative CAR in all 3 event windows. Benchmarked against the S&P Financials, the CARs of CBOE are -2.72%, -4.40% and -1.14% respectively; the CARs of ICE are -2.50%, -4.17%% and -3.17% respectively, and the CARs of NDAQ are -3.46%, -4.39% and -2.98% respectively. The CARs display similar negative magnitudes using the S&P 500 as the benchmark. Thus, we conclude that competing exchange operators' stock returns are negative upon SEC's announcement of the approval of IEX's incorporation.

To further examine the impact of lit speed bump implementation on short interest of stocks of extant exchange operators, we estimate the following models:

$$Short\ interest_{i,t} = \beta_0 + \beta_1 Lit\ speed\ bump_t + \sum_i^{\delta}\left(control\ variables_{i,t}\right) + \varepsilon_{i,t} \quad (18)$$

$$Short\ interest_{i,t} = \beta_0 + \beta_1 Lit\ speed\ bump + \beta_2 Dark\ speed\ bump_t + \sum_i^{\delta}(control\ variables_{i,t}) + \varepsilon_{i,t} \quad (19)$$

where $Short\ interest_{i,t}$ is mean short position of operator *i* in quarter *t*; Lit speed bump $_t$is a dummy variable that equals 1 in post-lit speed bump implementation period (Q4 2016 to Q2

2017), 0 otherwise; $Dark\ speed\ bump_t$ is a dummy variable that equals 1 in post-dark speed bump implementation period (Q1 2014 to Q2 2017), 0 otherwise; Control variables are the same as those in equation (14) and (15).

[Table 17 here]

We regress short interest on the lit speed bump dummy and same set of the controls, from Q1 2012 to Q2 2017. Table 17 Panel A reports that the stock of CBOE itself experiences a significant increase in short interest. As shown in Table 17 Panels B and C, lit speed bump does not impact short interest on the stocks of ICE and NDAQ because they announced plans to implement speed bumps as well in future. Because IEX with its speed bump attracts order flow and makes CBOE less attractive without a speed bump, short-sellers anticipate worsening performance of the CBOE and increase short selling activity. The differential impacts of speed bumps suggest that it is the speed bump decision which is the main driver of short sellers' decisions; not just the general competitive effect of a new entrant.

V. Conclusion

Against the background that high speed trading has greatly changed U.S. securities markets (O'Hara, 2015), we examine whether the introduction of IEX, a new stock exchange with a speed bump that slows down fast traders, and has a stated aim to create a fairer trading environment, can indeed bring any beneficial changes to the market. We document that upon the introduction of a lit speed bump, the performance of extant exchange operators with no actual or planned speed bumps became worse. In particular, CBOE which operated the BATS exchanges that were allegedly used by HFTs to detect informed traders' orders and implement profitable trading strategies to exploit slow traders on other exchanges, suffered the most. We find informed trading increased on standard exchanges after lit speed bump implementation. Short-sellers increased short selling of CBOE's stock after the implementation of the lit speed bump. Meanwhile, overall market quality improved with decreases in quoted spread, quote-to-trade ratio, cancel-to-trade ratio, order imbalance and proportion of flickering quotes, as well as increases in quoted depth and quote life. As a result, fundamentally informed trading measured by the odd lot rate increased. We also find that market activity intensified with more quotes and trades post-lit speed bump implementation. To reconcile improved market quality and market activity with worsened exchange operator performance, we further explore market share and short interest and find that CBOE's market share dropped significantly while IEX gained market share. These findings shed light on the implication of levelled speed in modern securities markets and has topical importance for regulatory policy given that other exchange operators such as the NYSE and NDAQ have requested the SEC to approve their plans to implement speed bumps in some of the exchanges they operate.

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Table 1 Descriptive statistics

This table presents descriptive statistics of exchange operator performance and sample selection. Panel A reports performance of CBOE Global Markets Inc.(CBOE), Intercontinental Exchange Inc. (ICE) and Nasdaq Inc (NDAQ), the 3 owners and operators of U.S. stock exchanges except Chicago Stock Exchange Inc. (CHX) and The Investors' Exchange LLC. (IEX) that are not publicly held in the sample period from Q1 2012 to Q2 2017. We report the mean of ROA calculated as net income divided by total assets, Tobin's Q calculated as market value of common shares divided by total assets, net income (in $ millions), transaction fees revenue calculated as transaction fees divided by revenue, EPS and short interest (in millions) for each of them in the sample period. Panel B reports sample selection for market quality. Sample firms are chosen based on the listed firms' market capitalization on August 24, 2016 based on the following criteria. First, the stocks must exist at the intersection of the DTAQ and CRSP databases. The stock must have closing price greater than $10 and less than $1,000 on August 24, 2016 and must be common stock whose CRSP share code is either 10 or 11. Stocks are then grouped as small, medium or large based on market capitalization. The top 50 stocks, based on market capitalization, from each grouping from the sample of 150 stocks considered in this study.

Panel A: Performance of exchange operators who own competing exchanges

	ROA	Tobin's Q	Net Income	Transaction fees revenue	EPS	Short Interest
CBOE (Operates NSX, EDGA, EDGX, BYX, BZX)	0.106	10.127	45.315	0.695	0.520	3.080
ICE (Operates NYSE MKT, NYSE, NYSE Arca)	0.004	0.351	246.121	0.284	0.468	14.779
NDAQ (Operates Nasdaq BX, Nasdaq, Nasdaq PSX)	0.008	0.623	93.864	0.396	0.563	3.533
Average	**0.039**	**3.7**	**128.433**	**0.486**	**0.517**	**7.131**

Panel B: Sample selection for market quality of firms that trade on exchanges

	No. of Firms	Average market capitalization (in $millions)	Volume (in millions)	Return
Full sample	150	1,504	572	-0.52%
By firm size				
Small	50	76	9	0.12%
Medium	50	898	661	-0.88%
Large	50	3,539	1,046	-0.78%
By listing exchange				
New York Stock Exchange	47	2,257	729	-0.50%
American Stock Exchange	4	53	3	-1.32%
Nasdaq Stock Exchange	99	1,205	521	-0.49%

Table 2 Reaction speed around lit speed bump implementation for the firms that trade on the exchanges

This table reports the proportion of reaction speed on Nasdaq following a trade on a remote market around lit speed bump implementation. Reaction speed is measured as the difference between the time a limit order on Nasdaq reacts (i.e. is revised or cancelled) and the time that the last order was previously executed on a remote market. We split reaction speed into 1, 2, 3, 4, 5, 10, 100 and 100+ millisecond time buckets. We then calculate the proportion of reaction speed in each time bucket. Panel A of the table reports summary statistics of limit order reaction speed for the 150 sample stocks on August 12, 15, 16, 17 and 18 2016 and September 6, 7, 8, 9 and 12, 2016. The pre-lit speed bump implementation and post-lit speed bump implementation statistics are reported in Panel B. Event coefficients from the multivariate regression models discussed below are reported in Panel C. In columns 1 through 6, we report cross-sectional summary statistics for the full sample and the mean for the pre-lit speed bump implementation and post-lit speed bump implementation periods. In columns 7 and 8, we report the differences between the post-lit speed bump implementation and pre-lit speed bump implementation statistics, respectively, in original units and as proportion of the pre-lit speed bump implementation value. The asterisks ***, ** and * in column 7 and 8 denote 1%, 5% and 10% statistical significance of the difference in mean t-test. Columns 9 and 10 contain coefficient estimates β_1 and β_2 from the following regression models:

$$Reaction\ speed\ bucket\ proportion_{i,t} = \beta_0 + \beta_1 Lit\ speed\ bump_t + \delta_1 Iprice_{i,t} + \delta_2 Mcap_{i,t} + \varepsilon_{i,t}$$

and

$$Reaction\ speed\ bucket\ proportion_{i,t} = \beta_0 + \beta_2 Lit\ speed\ bump_t + \delta_1 Iprice_{i,t} + \delta_2 Mcap_{i,t} + \delta_3 Volt_{i,t} + \delta_4 Turn_{i,t} + \varepsilon_{i,t}$$

where $\text{Reaction speed}_{i,t}$ is the proportion of reaction (i.e. revisions and cancellations) speed in each time bucket for stock i on day t. Lit speed bump_t is a dummy equals 1 post-lit speed bump implementation, 0 otherwise. $\text{Iprice}_{i,t}$ is the inverse of the stock price, $\text{Mcap}_{i,t}$ is market capitalization, $\text{Volt}_{i,t}$ is volatility, the daily high minus daily low stock price, scaled by the high price, and $\text{Turn}_{i,t}$ is turnover. The regressions are estimated with stock fixed effect. The asterisks ***, ** and * in columns 9 and 10 denote statistical significance of β_1 and β_2 coefficient estimates at 1%, 5% and 10%.

	Panel A				Panel B				Panel C	
	mean	25%	median	75%	Pre	Post	Post-pre	%	β_1	β_2
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
1 millisecond	0.450	0.430	0.441	0.461	0.467	0.433	-0.034***	-7%***	-0.0340***	-0.0343***
2 milliseconds	0.063	0.059	0.063	0.066	0.059	0.066	0.007***	12%***	0.00728***	0.00734***
3 milliseconds	0.025	0.023	0.024	0.026	0.023	0.026	0.003**	11%**	0.00266***	0.00259***
4 milliseconds	0.015	0.015	0.015	0.016	0.015	0.016	0.001**	9%**	0.00140***	0.00136***
5 milliseconds	0.014	0.013	0.013	0.014	0.013	0.014	0.001	9%	0.00120***	0.00113***
10 milliseconds	0.034	0.033	0.033	0.036	0.033	0.036	0.003*	9%*	0.00304***	0.00294***
100 milliseconds	0.125	0.116	0.120	0.135	0.118	0.125	0.007**	6%**	0.0134***	0.0132***
100+ milliseconds	0.274	0.263	0.274	0.283	0.272	0.277	0.005	2%	0.00500***	0.00576***

Table 3 Cancellation speed for a given order around lit speed bump implementation for the firms that trade on the exchanges

This table reports the proportion of cancellation speed on Nasdaq around lit speed bump implementation. Cancellation speed for a given order is measured as the difference between the time a limit order is outstanding on Nasdaq until it is revised or cancelled on Nasdaq. We split cancel speed into 1, 2, 3, 4, 5, 10, 100 and 100+ millisecond time buckets. We then calculate the proportion of quote life in each time bucket. Panel A of the table reports summary statistics of cancellation speed for the 150 sample stocks on August 12, 15, 16, 17 and 18 2016 and September 6, 7, 8, 9 and 12, 2016. The pre-lit speed bump implementation and post-lit speed bump implementation statistics are reported in Panel B. Event coefficients from the multivariate regression models discussed below are reported in Panel C. In columns 1 through 6, we report cross-sectional summary statistics for the full sample and the mean for the pre-lit speed bump implementation and post-lit speed bump implementation periods. In columns 7 and 8, we report the differences between the post-lit speed bump implementation and pre-lit speed bump implementation statistics, respectively, in original units and as proportion of the pre-lit speed bump implementation value. The asterisks ***, ** and * in column 7 and 8 denote 1%, 5% and 10% statistical significance of the difference in mean t-test. Columns 9 and 10 contain coefficient estimates β_1 and β_2 from the following regression models:

$$Cancellation\ speed\ bucket\ proportion\ _{i,t} = \beta_0 + \beta_1 Lit\ speed\ bump_t + \delta_1 Iprice_{i,t} + \delta_2 Mcap_{i,t} + \varepsilon_{i,t}$$

and

$$Cancellation\ speed\ bucket\ proportion_{i,t} = \beta_0 + \beta_2 Lit\ speed\ bump_t + \delta_1 Iprice_{i,t} + \delta_2 Mcap_{i,t} + \delta_3 Volt_{i,t} + \delta_4 Turn_{i,t} + \varepsilon_{i,t}$$

where $\text{Cancellation speed proportion}_{\text{i,t}}$ is the proportion of revisions and cancellations speed in each time bucket for stock i on day t. $\text{Lit speed bump}_{\text{t}}$ is a dummy equals 1 post-lit speed bump implementation, 0 otherwise. $\text{Iprice}_{\text{i,t}}$ is the inverse of the stock price, $\text{Mcap}_{\text{i,t}}$ is market capitalization, $\text{Volt}_{\text{i,t}}$ is volatility, the daily high minus daily low stock price, scaled by the high price, and $\text{Turn}_{\text{i,t}}$ is turnover. The regressions are estimated with stock fixed effect. The asterisks ***, ** and * in columns 9 and 10 denote statistical significance of β_1 and β_2 coefficient estimates at 1%, 5% and 10%.

	Panel A				Panel B				Panel C	
	mean	25%	median	75%	Pre	Post	Post-pre	%	β_1	β_2
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
1 millisecond	0.127	0.122	0.127	0.130	0.131	0.124	-0.007*	-6%*	-0.00629***	-0.00627***
2 milliseconds	0.030	0.028	0.029	0.033	0.028	0.033	0.005**	16%**	0.00451***	0.00453***
3 milliseconds	0.014	0.011	0.012	0.015	0.012	0.016	0.005*	42%*	0.00482***	0.00479***
4 milliseconds	0.005	0.004	0.005	0.005	0.004	0.005	0.001*	13%*	0.000612***	0.000602***
5 milliseconds	0.005	0.004	0.006	0.006	0.005	0.006	0.001*	22%*	0.00108***	0.00107***
10 milliseconds	0.018	0.017	0.017	0.018	0.017	0.019	0.002*	14%*	0.00245***	0.00242***
100 milliseconds	0.070	0.067	0.070	0.075	0.071	0.069	-0.002	-2%	-0.00133***	-0.00146***
100+ milliseconds	0.730	0.721	0.730	0.738	0.732	0.728	-0.004	-1%	-0.00444***	-0.00431***

Table 4 Fill speed around lit speed bump implementation for the firms that trade on the exchanges

This table reports the proportion of filled orders speed on Nasdaq around lit speed bump implementation. Fill speed for a given order is measured as the difference between the time a limit order is outstanding on Nasdaq until it is executed. We split fill speed into 1, 2, 3, 4, 5, 10, 100 and 100+ millisecond time buckets. We then calculate the proportion of filled orders in each time bucket. Panel A of the table reports summary statistics of fill speed for the 150 sample stocks on August 12, 15, 16, 17 and 18 2016 and September 6, 7, 8, 9 and 12, 2016. The pre-lit speed bump implementation and post-lit speed bump implementation statistics are reported in Panel B. Event coefficients from the multivariate regression models discussed below are reported in Panel C. In columns 1 through 6, we report cross-sectional summary statistics for the full sample and the mean for the pre-lit speed bump implementation and post-lit speed bump implementation periods. In columns 7 and 8, we report the differences between the post-lit speed bump implementation and pre-lit speed bump implementation statistics, respectively, in original units and as proportion of the pre-lit speed bump implementation value. The asterisks ***, ** and * in column 7 and 8 denote 1%, 5% and 10% statistical significance of the difference in mean t-test. Columns 9 and 10 contain coefficient estimates β_1 and β_2 from the following regression models:

$$Fill\ speed\ bucket\ proportion_{\ i,t} = \beta_0 + \beta_1 Lit\ speed\ bump_t + \delta_1 Iprice_{i,t} + \delta_2 Mcap_{i,t} + \varepsilon_{i,t}$$

and

$$Fill\ speed\ bucket\ proportion_{i,t} = \beta_0 + \beta_2 Lit\ speed\ bump_t + \delta_1 Iprice_{i,t} + \delta_2 Mcap_{i,t} + \delta_3 Volt_{i,t} + \delta_4 Turn_{i,t} + \varepsilon_{i,t}$$

where $\text{Fill speed proportion}_{i,t}$ is the proportion of filled orders speed in each time bucket for stock i on day t. Lit speed bump_t is a dummy equals 1 post-lit speed bump implementation, 0 otherwise. $\text{Iprice}_{i,t}$ is the inverse of the stock price, $\text{Mcap}_{i,t}$ is market capitalization, $\text{Volt}_{i,t}$ is volatility, the daily high minus daily low stock price, scaled by the high price, and $\text{Turn}_{i,t}$ is turnover. The regressions are estimated with stock fixed effect. The asterisks ***, ** and * in columns 9 and 10 denote statistical significance of β_1 and β_2 coefficient estimates at 1%, 5% and 10%.

	Panel A				Panel B				Panel C	
	mean	25%	median	75%	Pre	Post	Post-pre	%	β_1	β_2
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
1 millisecond	0.071	0.067	0.070	0.074	0.072	0.070	-0.002***	-3%***	-0.00194***	-0.00196***
2 milliseconds	0.017	0.015	0.016	0.018	0.018	0.015	-0.002***	-14%***	-0.00238***	-0.00239***
3 milliseconds	0.007	0.007	0.007	0.008	0.008	0.007	-0.001***	-10%***	-0.000763***	-0.000770***
4 milliseconds	0.005	0.004	0.005	0.005	0.005	0.005	0.000***	5%***	0.000203***	0.000202***
5 milliseconds	0.004	0.003	0.004	0.004	0.003	0.004	0.000***	13%***	0.000446***	0.000442***
10 milliseconds	0.011	0.010	0.012	0.012	0.011	0.012	0.001***	10%***	0.00109***	0.00109***
100 milliseconds	0.042	0.039	0.044	0.045	0.041	0.043	0.002***	5%***	0.00220***	0.00216***
100+ milliseconds	0.844	0.841	0.842	0.852	0.843	0.844	0.001***	0%***	0.00135**	0.00130**

Table 5 NBBO revision speed around lit speed bump implementation for the firms that trade on the exchanges

This table reports the proportion of NBBO revision speed around lit speed bump implementation. NBBO revision speed is measured as the difference between the time a NBBO is posted and the time the next NBBO is posted. We split NBBO revision speed into 1, 2, 3, 4, 5, 10, 100 and 100+ millisecond time buckets. We then calculate the proportion of NBBO revision speed in each time bucket. Panel A of the table reports summary statistics of NBBO revision speed for the 150 sample stocks on August 12, 15, 16, 17 and 18 2016 and September 6, 7, 8, 9 and 12, 2016. The pre-lit speed bump implementation and post-lit speed bump implementation statistics are reported in Panel B. Event coefficients from the multivariate regression models discussed below are reported in Panel C. In columns 1 through 6, we report cross-sectional summary statistics for the full sample and the mean for the pre-lit speed bump implementation and post-lit speed bump implementation periods. In columns 7 and 8, we report the differences between the post-lit speed bump implementation and pre-lit speed bump implementation statistics, respectively, in original units and as proportion of the pre-lit speed bump implementation value. The asterisks ***, ** and * in column 7 and 8 denote 1%, 5% and 10% statistical significance of the difference in mean t-test. Columns 9 and 10 contain coefficient estimates β_1 and β_2 from the following regression models:

$$NBBO\ revision\ speed\ bucket\ proportion_{i,t} = \beta_0 + \beta_1 Lit\ speed\ bump_t + \delta_1 Iprice_{i,t} + \delta_2 Mcap_{i,t} + \varepsilon_{i,t}$$

and

$$NBBO\ revision\ speed\ bucket\ proportion_{i,t} = \beta_0 + \beta_2 Lit\ speed\ bump_t + \delta_1 Iprice_{i,t} + \delta_2 Mcap_{i,t} + \delta_3 Volt_{i,t} + \delta_4 Turn_{i,t} + \varepsilon_{i,t}$$

where NBBO revision speed $\mathrm{proportion}_{i,t}$ is the proportion of NBBO revision speed in each time bucket for stock i on day t. Lit speed bump_t is a dummy equals 1 post-lit speed bump implementation, 0 otherwise. $\mathrm{Iprice}_{i,t}$ is the inverse of the stock price, $\mathrm{Mcap}_{i,t}$ is market capitalization, $\mathrm{Volt}_{i,t}$ is volatility, the daily high minus daily low stock price, scaled by the high price, and $\mathrm{Turn}_{i,t}$ is turnover. The regressions are estimated with stock fixed effect. The asterisks ***, ** and * in columns 9 and 10 denote statistical significance of β_1 and β_2 coefficient estimates at 1%, 5% and 10%.

	Panel A				Panel B				Panel C	
	Mean	25%	median	75%	Pre	Post	Post-pre	%	β_1	β_2
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
1 millisecond	0.497	0.483	0.505	0.511	0.511	0.484	0.027***	-5%***	-0.0276***	-0.0274***
2 milliseconds	0.055	0.048	0.059	0.062	0.048	0.062	0.014***	29%***	0.0137***	0.0137***
3 milliseconds	0.024	0.021	0.024	0.026	0.021	0.026	0.005***	24%***	0.00485***	0.00481***
4 milliseconds	0.015	0.013	0.014	0.016	0.014	0.016	0.002***	14%***	0.00204***	0.00201***
5 milliseconds	0.012	0.011	0.011	0.012	0.011	0.012	0.001***	9%***	0.00129***	0.00127***
10 milliseconds	0.031	0.028	0.029	0.031	0.028	0.033	0.005***	18%***	0.00469***	0.00463***
100 milliseconds	0.095	0.089	0.091	0.095	0.090	0.100	0.01***	11%***	0.00990***	0.00973***
100+ milliseconds	0.272	0.266	0.273	0.278	0.277	0.268	-0.009***	-3%***	-0.00882***	-0.00871***

Table 6 Trading speed after NBBO revision around lit speed bump implementation for the firms that trade on the exchanges

This table reports the proportion of trading speed after NBBO revision around lit speed bump implementation. Trading speed after NBBO revision is measured as the difference between the time a NBBO is posted and the time a trade is executed subsequently. We split trading speed into 1, 2, 3, 4, 5, 10, 100 and 100+ millisecond time buckets. We then calculate the proportion of trading speed in each time bucket. Panel A of the table reports summary statistics of trading speed after NBBO revision for the 150 sample stocks on August 12, 15, 16, 17 and 18 2016 and September 6, 7, 8, 9 and 12, 2016. The pre-lit speed bump implementation and post-lit speed bump implementation statistics are reported in Panel B. Event coefficients from the multivariate regression models discussed below are reported in Panel C. In columns 1 through 6, we report cross-sectional summary statistics for the full sample and the mean for the pre-lit speed bump implementation and post-lit speed bump implementation periods. In columns 7 and 8, we report the differences between the post-lit speed bump implementation and pre-lit speed bump implementation statistics, respectively, in original units and as proportion of the pre-lit speed bump implementation value. The asterisks ***, ** and * in column 7 and 8 denote 1%, 5% and 10% statistical significance of the difference in mean t-test. Columns 9 and 10 contain coefficient estimates $\beta_1$and β_2 from the following regression models:

$$Post\ NBBO\ revision\ trading\ speed\ bucket\ proportion\ _{i,t} = \beta_0 + \beta_1 Lit\ speed\ bump_t + \delta_1 Iprice_{i,t} + \delta_2 Mcap_{i,t} + \varepsilon_{i,t}$$

and

$$Post\ NBBO\ revision\ trading\ speed\ bucket\ proportiont = \beta_0 + \beta_2 Lit\ speed\ bump_t + \delta_1 Iprice_{i,t} + \delta_2 Mcap_{i,t} + \delta_3 Volt_{i,t} + \delta_4 Turn_{i,t} + \varepsilon_{i,t}$$

where Trading speed after NBBO revision $\mathrm{proportion}_{i,t}$ is the proportion of trading speed after NBBO revision in each time bucket for stock i on day t. Lit speed bump_t is a dummy equals 1 post-lit speed bump implementation, 0 otherwise. $\mathrm{Iprice}_{i,t}$ is the inverse of the stock price, $\mathrm{Mcap}_{i,t}$ is market capitalization, $\mathrm{Volt}_{i,t}$ is volatility, the daily high minus daily low stock price, scaled by the high price, and $\mathrm{Turn}_{i,t}$ is turnover. The regressions are estimated with stock fixed effect. The asterisks ***, ** and * in columns 9 and 10 denote statistical significance of $\beta_1$and β_2 coefficient estimates at 1%, 5% and 10%.

	Panel A				Panel B				Panel C	
	mean	25%	median	75%	Pre	Post	Post-pre	%	β_1	β_2
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
1 millisecond	0.574	0.564	0.577	0.581	0.578	0.570	-0.007***	-1%***	-0.00772***	-0.00755***
2 milliseconds	0.028	0.027	0.028	0.029	0.028	0.028	0.000	0%	0.0000386	0.0000126
3 milliseconds	0.015	0.015	0.015	0.016	0.015	0.016	0.000***	3%***	0.000415***	0.000392***
4 milliseconds	0.010	0.010	0.010	0.010	0.010	0.010	0.000***	2%***	0.000265***	0.000250***
5 milliseconds	0.008	0.008	0.008	0.008	0.008	0.008	0.000***	3%***	0.000292***	0.000281***
10 milliseconds	0.026	0.025	0.026	0.027	0.026	0.026	0.000***	-0%***	-0.000222***	-0.000242***
100 milliseconds	0.076	0.072	0.074	0.076	0.073	0.079	0.006***	8%***	0.00637***	0.00626***
100+ milliseconds	0.263	0.259	0.259	0.265	0.262	0.263	0.001**	0%**	0.000616	0.000624

Table 7 NBBO revision speed after a trade around lit speed bump implementation for the firms that trade on the exchanges

This table reports the proportion of NBBO revision speed after a trade around lit speed bump implementation. NBBO revision speed is measured as the difference between the time a trade is executed and the time a new NBBO is posted subsequently. We split NBBO revision speed into 1, 2, 3, 4, 5, 10, 100 and 100+ millisecond time buckets. We then calculate the proportion of NBBO revision speed in each time bucket. Panel A of the table reports summary statistics of NBBO revision speed after trade execution for the 150 sample stocks on August 12, 15, 16, 17 and 18 2016 and September 6, 7, 8, 9 and 12, 2016. The pre-lit speed bump implementation and post-lit speed bump implementation statistics are reported in Panel B. Event coefficients from the multivariate regression models discussed below are reported in Panel C. In columns 1 through 6, we report cross-sectional summary statistics for the full sample and the mean for the pre-lit speed bump implementation and post-lit speed bump implementation periods. In columns 7 and 8, we report the differences between the post-lit speed bump implementation and pre-lit speed bump implementation statistics, respectively, in original units and as proportion of the pre-lit speed bump implementation value. The asterisks ***, ** and * in column 7 and 8 denote 1%, 5% and 10% statistical significance of the difference in mean t-test. Columns 9 and 10 contain coefficient estimates β_1 and β_2 from the following regression models:

$$Post\ trade\ NBBO\ revision\ speed\ bucket\ proportion\ _{i,t} = \beta_0 + \beta_1 Lit\ speed\ bump_t + \delta_1 Iprice_{i,t} + \delta_2 Mcap_{i,t} + \varepsilon_{i,t}$$

and

$$Post\ trade\ NBBO\ revision\ speed\ bucket\ proportion_{i,t} = \beta_0 + \beta_2 Lit\ speed\ bump_t + \delta_1 Iprice_{i,t} + \delta_2 Mcap_{i,t} + \delta_3 Volt_{i,t} + \delta_4 Turn_{i,t} + \varepsilon_{i,t}$$

where $\text{Post trade NBBO revision speed bucket proportion}_{i,t}$ is the proportion of post trade NBBO revision in each time bucket for stock i on day t. Lit speed bump_t is a dummy equals 1 post-lit speed bump implementation, 0 otherwise. $\text{Iprice}_{i,t}$ is the inverse of the stock price, $\text{Mcap}_{i,t}$ is market capitalization, $\text{Volt}_{i,t}$ is volatility, the daily high minus daily low stock price, scaled by the high price, and $\text{Turn}_{i,t}$ is turnover. The regressions are estimated with stock fixed effect. The asterisks ***, ** and * in columns 9 and 10 denote statistical significance of β_1 and β_2 coefficient estimates at 1%, 5% and 10%.

	Panel A				Panel B				Panel C	
	mean	25%	median	75%	Pre	Post	Post-pre	%	β_1	β_2
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
1 millisecond	0.641	0.636	0.639	0.643	0.645	0.637	-0.008***	-1%***	-0.00760***	-0.00768***
2 milliseconds	0.040	0.039	0.039	0.042	0.039	0.041	0.002***	6%***	0.00249***	0.00247***
3 milliseconds	0.016	0.015	0.015	0.016	0.015	0.017	0.001***	9%***	0.00143***	0.00141***
4 milliseconds	0.010	0.009	0.009	0.010	0.009	0.010	0.001***	7%***	0.000680***	0.000666***
5 milliseconds	0.008	0.008	0.008	0.008	0.008	0.008	0.000***	6%***	0.000478***	0.000464***
10 milliseconds	0.022	0.021	0.022	0.023	0.022	0.022	0.001***	3%***	0.000715***	0.000698***
100 milliseconds	0.068	0.066	0.068	0.070	0.066	0.069	0.003***	4%***	0.00274***	0.00272***
100+ milliseconds	0.195	0.187	0.198	0.201	0.196	0.195	-0.001	-0%	-0.000922**	-0.000779*

Table 8 Market quality and informed trading around lit speed bump implementation for the firms that trade on the exchanges

This table reports market quality and informed trading around lit speed bump implementation for firms trading on the exchanges. Quoted spread is computed as the difference between the national best ask and national best bid. Best bid depth is computed as the product of best bid price and best bid size multiplied by time-weight. Best ask depth is computed as the product of best ask price and best ask size multiplied by time-weight. Cancel to trade is calculated as the ratio between number of cancels and number of lit trades that is the difference between number of total trades and number of hidden trades. Order imbalance is calculated as the absolute value of the ratio between the difference between the number of buy orders and the number of sell orders and the sum of the number of buy orders and the number of sell orders. Odd lot rate is calculated as the ratio between number of odd lot trade and the number of trades from order-based exchanges multiplied by 100. ISO rate is computed as the ratio between number of ISO and number of trades. All of the abovementioned metrics are computed on the intraday basis and then converted into daily aggregates. Panel A of the table reports summary statistics of market quality and informed trading metrics for the 150 sample stocks on August 12, 15, 16, 17 and 18 2016 and September 6, 7, 8, 9 and 12, 2016. The pre-lit speed bump implementation and post-lit speed bump implementation statistics are reported in Panel B. Event coefficients from the multivariate regression models discussed below are reported in Panel C. In columns 1 through 6, we report cross-sectional summary statistics for the full sample and the mean for the pre-lit speed bump implementation and post-lit speed bump implementation periods. In columns 7 and 8, we report the differences between the post-lit speed bump implementation and pre-lit speed bump implementation statistics, respectively, in original units and as proportion of the pre-lit speed bump implementation value. The asterisks ***, ** and * in column 7 and 8 denote 1%, 5% and 10% statistical significance of the difference in mean t-test. Columns 9 and 10 contain coefficient estimates β_1 and β_2 from the following regression models:

$$Market\ quality\ and\ informed\ trading_{i,t} = \beta_0 + \beta_1 Lit\ speed\ bump_t + \delta_1 Iprice_{i,t} + \delta_2 Mcap_{i,t} + \varepsilon_{i,t}$$

and

$$Market\ quality\ and\ informed\ trading_{i,t} = \beta_0 + \beta_2 Lit\ speed\ bump_t + \delta_1 Iprice_{i,t} + \delta_2 Mcap_{i,t} + \delta_3 Volt_{i,t} + \delta_4 Turn_{i,t} + \varepsilon_{i,t}$$

where $\text{Market quality}_{i,t}$ is one of the market quality and informed trading metrics identified above for stock i on day t, Lit speed bump_t is a dummy equals 1 post-lit speed bump implementation, 0 otherwise. $\text{Iprice}_{i,t}$ is the inverse of the stock price, $\text{Mcap}_{i,t}$ is market capitalization, $\text{Volt}_{i,t}$ is volatility, the daily high minus daily low stock price, scaled by the high price, and $\text{Turn}_{i,t}$ is turnover. The regressions are estimated with stock fixed effect. The asterisks ***, ** and * in columns 9 and 10 denote statistical significance of β_1 and β_2 coefficient estimates at 1%, 5% and 10%.

	Panel A Summary Statistics				Panel B: mean changes around IEX became exchange				Panel C: Regression	
	mean	25%	median	75%	pre	post	post-pre	%	β_1	β_2
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Market quality metrics										
Quoted Spread	0.13	0.02	0.05	0.15	0.13	0.12	-0.01	-11%	-0.0149*	-0.0137*
Best Bid Depth	305.32	56.86	111.79	211.34	220	391	171*	78%*	151.1**	151.6**
Best Ask Depth	276.15	57.44	117.83	234.66	206	346	140**	68%**	121.2***	118.6***
Cancel to Trade	92.98	18.05	25.86	45.30	95.05	91.03	-4.02	-4%	-227.3*	-208.0*
Order imbalance	0.18	0.05	0.11	0.21	0.19	0.17	-0.02	-12%**	-0.0191**	-0.009
Informed trading metrics										
Odd lot rate	37.55	25.07	35.85	48.15	35.27	39.76	4.49***	13%***	5.453**	8.569***
ISO/Total	0.10	0.00	0.00	0.23	0.11	0.10	-0.01	-10%	0.000814	-0.00302

Table 9 Changes of follow-on order strategy pre- and post- list speed bump implementation

This table reports the odd lot rate for the 150 sample stocks on August 12, 15, 16, 17 and 18 2016 (pre-lit speed bump implementation) and September 6, 7, 8, 9 and 12, 2016 (post-lit speed bump implementation) by exchanges and their operators. Odd lot rate is calculated as the ratio between number of odd lot trade and the number of trades from order-based exchanges multiplied by 100. Odd lot rate is computed on the intraday basis and then converted into daily aggregates. The asterisks ***, ** and * in denote 1%, 5% and 10% statistical significance of the difference in mean according to t- test.

		Odd lot rate			
Owner	Exchange	Pre	Post	Post-pre	%
CBOE		16.76	18.62	1.86***	11%***
	C. NSX	17.61	10.41	-7.20	-41%
	J. EDGA	16.77	17.66	0.88	5%
	K. EDGX	15.24	19.38	4.14***	27%***
	Y. BYX	18.01	20.02	2.00**	11%**
	Z. BZX	17.13	18.34	1.21	7%
ICE		15.59	16.94	1.34	9%
	A. NYSE MKT	27.10	24.11	-2.99	-11%
	N. NYSE	9.58	9.50	-0.07	-1%
	P. NYSE Arca	17.02	19.22	2.20*	13%*
NDAQ		17.71	18.23	0.53	3%
	B. Nasdaq BX	18.60	18.96	0.37	2%
	Q. Nasdaq Tape C	20.80	21.83	1.03	5%
	T. Nasdaq Tape AB	20.11	20.94	0.83	4%
	X. Nasdaq PSX	12.93	12.82	-0.11	-1%
N/A	D. FINRA	7.11	6.53	-0.58	-8%
N/A	M. CHX	50.39	32.46	17.92	36%
N/A	V. IEX	N/A	7.82	N/A	N/A

Table 10 Informed trading around lit speed bump implementation for the firms that trade on the exchanges by exchanges and their operators

This table reports the parameters estimated in the first-order autoregressions for each trading venue's trades on August 18, 2016 (before IEX became a stock exchange) and on September 12, 2016 (After IEX became a stock exchange).

Exchange	August 2016	September 2016	Decreased
A. NYSE MKT	-0.05	1.208*	No
B. Nasdaq BX	0.111	0.068	Yes
C. NSX	0.399	-0.137	Yes
D. FINRA	-0.154***	-0.026	No
J. EDGA	-0.398***	-0.671***	Yes
K. EDGX	0.388***	0.134***	Yes
M. CHX	0.661	1.452***	No
N. NYSE	0.246***	-0.115*	Yes
P. NYSE Arca	0.15***	-0.072**	Yes
Q. Nasdaq Tape C	0.124***	0.254***	No
T. Nasdaq Tape AB	0.675***	0.121***	Yes
V. IEX	0	-0.203**	Not applicable
X. Nasdaq PSX	0.211	0.004	Yes
Y. BYX	-0.204***	-0.221***	Yes
Z. BZX	0.135***	0.068*	Yes

Table 11 Quote and trade activity

This table reports quote and trade activity consequence around lit speed bump implementation. Quotes and trades are log-transformed number of quotes and number of trades respectively. QTR (quote-to-trade ratio) is log-transformed number of quotes divided by log-transformed number of trades. Panel A of the table reports summary statistics of quotes, trades and QTR for the 150 sample stocks on August 12, 15, 16, 17 and 18 2016 and September 6, 7, 8, 9 and 12, 2016. The pre-lit speed bump implementation and post-lit speed bump implementation statistics are reported in Panel B. Event coefficients from the multivariate regression models discussed below are reported in Panel C. In columns 1 through 6, we report cross-sectional summary statistics for the full sample and the mean for the pre-lit speed bump implementation and post-lit speed bump implementation periods. In columns 7 and 8, we report the differences between the post-lit speed bump implementation and pre-lit speed bump implementation statistics, respectively, in original units and as proportion of the pre-lit speed bump implementation value. The asterisks ***, ** and * in column 7 and 8 denote 1%, 5% and 10% statistical significance of the difference in mean t-test. Columns 9 and 10 contain coefficient estimates β_1 and β_2 from the following regression models:

$$Quote\ and\ trade\ activity_{i,t} = \beta_0 + \beta_1 Lit\ speed\ bump_t + \delta_1 Iprice_{i,t} + \delta_2 Mcap_{i,t} + \varepsilon_{i,t}$$

and

$$Quote\ and\ trade\ activity_{i,t} = \beta_0 + \beta_2 Lit\ speed\ bump_t + \delta_1 Iprice_{i,t} + \delta_2 Mcap_{i,t} + \delta_3 Volt_{i,t} + \delta_4 Turn_{i,t} + \varepsilon_{i,t}$$

where $\text{Quote and trade activity}_{i,t}$ is one of the following variables for firm i on day t: quotes, defined as log-transformed number of quotes, trades, defined as log-transformed number of trades and QTR, defined as log-transformed number of quotes divided by log-transformed number of trades. Lit speed bump_t is a dummy equals 1 post-lit speed bump implementation, 0 otherwise. $\text{Iprice}_{i,t}$ is the inverse of the stock price, $\text{Mcap}_{i,t}$ is market capitalization, $\text{Volt}_{i,t}$ is volatility, the daily high minus daily low stock price, scaled by the high price, and $\text{Turn}_{i,t}$ is turnover. The regressions are estimated with stock fixed effect. The asterisks ***, ** and * in columns 9 and 10 denote statistical significance of β_1 and β_2 coefficient estimates at 1%, 5% and 10%.

	Panel A				Panel B				Panel C	
	mean	25%	median	75%	Pre	Post	Post-pre	%	β_1	β_2
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Quotes	9.60	7.42	10.31	11.53	9.40	9.80	0.40**	4%**	0.398***	0.292***
Trades	6.61	4.32	7.43	8.54	6.44	6.78	0.34*	5%*	0.325***	0.0917***
QTR	1.58	1.33	1.41	1.63	1.64	1.52	-0.11**	-7%**	-0.114***	-0.00518

Table 12 Competition among exchanges

This table summarizes market share based on volume, number of trades, number of national best bid (NBB) and number of national best offer (NBO) by exchange and their operators. Volume is the total volume of trades executed on the exchange. No. of Trade is the number of trade executed on the exchange. For Panel A and B, we take 5 trading days (September 6, 7, 8, 9, 12, 2016) just after IEX were able to trade all stocks and 5 trading days (August 25, 28, 29, 30, 31, 2017) about one year after IEX became a stock exchange to compare. Panel A reports the market share based on the mean of volume on the 5 days in September 2016, the 5 days in August 2017 and their difference. Panel B reports market share based on the mean of no. of trades on the 5 days in September 2016, the 5 days in August 2017 and their difference. For Panel C and D, we take 5 trading days (August 12, 15, 16, 17, 18, 2016) just before IEX were able to trade all stocks and 5 trading days (September 06, 07, 08, 09, 12, 2016) just after IEX were able to trade all stocks. Panel C reports market share based on the mean of NBB on the 5 days in August 2016, the 5 days in September 2016 and their difference. Panel D reports market share based on the mean of NBO on the 5 days in August 2016, the 5 days in September 2016 and their difference. The asterisks ***, ** and * in Panel C denote 1%, 5% and 10% statistical significance of the difference in mean according to t- test.

		Panel A: Market share based on volume			Panel B: Market share based on no. of trades		
Owner	Exchange	September2016	August2017	Difference	September2016	August2017	Difference
CBOE		23.33%	18.43%	-4.90%***	30.34%	27.71%	-2.63%***
	C. NSX	0.01%	N/A	N/A	0.01%	N/A	N/A
	J. EDGA	3.04%	1.29%	-1.75%***	4.29%	2.26%	-2.03%***
	K. EDGX	7.11%	6.66%	-0.45%	8.42%	8.57%	0.15%
	Y. BYX	5.60%	4.99%	-0.61%	7.90%	8.39%	0.50%
	Z. BZX	7.57%	5.49%	-2.08%***	9.73%	8.49%	-1.24%***
ICE		16.41%	19.29%	2.88%	16.50%	15.21%	-1.29%*
	A. NYSE MKT	0.10%	0.14%	0.04%	0.08%	0.26%	0.18%***
	N. NYSE	8.41%	12.90%	4.49%**	6.39%	5.68%	-0.71%
	P. NYSE Arca	7.90%	6.26%	-1.65%***	10.03%	9.27%	-0.76%***
NDAQ		23.41%	26.23%	2.82%	30.20%	32.29%	2.08%*
	B. Nasdaq BX	3.67%	3.77%	0.09%	5.29%	6.92%	1.63%***
	Q. Nasdaq Tape C	14.33%	17.82%	3.49%	17.81%	17.46%	-0.35%
	T. Nasdaq Tape AB	4.42%	4.03%	-0.39%	5.97%	6.84%	0.88%
	X. Nasdaq PSX	0.99%	0.61%	-0.37%***	1.14%	1.06%	-0.08%*
N/A	D. FINRA	34.64%	33.44%	-1.19%	21.10%	21.89%	0.79%
N/A	M. CHX	0.08%	0.02%	-0.06%	0.00%	0.01%	0.00%***

N/A	V. IEX	2.13%	2.58%	0.46%*	1.85%	2.90%	1.05%***

		Panel C: Market share based on number of NBB			Panel D: Market share based on number of NBO		
Owner	Exchange	September2016	August2017	Difference	September2016	August2017	Difference
CBOE		31.36%	14.77%	-16.59%***	31.49%	15.26%	-16.23%***
	C. NSX	0.25%	N/A	N/A	0.25%	N/A	N/A
	J. EDGA	4.29%	0.36%	-3.93%***	4.32%	0.43%	-3.89***
	K. EDGX	7.11%	5.39%	-1.72%	7.07%	5.84%	1.23%
	Y. BYX	9.27%	2.52%	-6.76%***	9.29%	2.64%	-6.65***
	Z. BZX	10.44%	6.51%	-3.93%**	10.56%	6.35%	-4.21%**
ICE		29.43%	37.03%	7.60%***	29.33%	37.33%	8.00%***
	A. NYSE MKT	0.21%	0.14%	-0.07%	0.21%	0.13%	-0.07%
	N. NYSE	14.03%	29.09%	15.06%***	14.11%	29.51%	15.40%***
	P. NYSE Arca	15.19%	7.80%	-7.39%***	15.01%	7.68%	-7.33%***
NDAQ		36.23%	47.38%	11.15%***	36.25%	46.58%	10.33%***
	B. Nasdaq BX	8.66%	1.97%	-6.69%***	8.65%	1.99%	-6.66%***
	Q. Nasdaq Tape C	5.95%	37.74%	31.79%***	6.01%	37.18%	31.17%***
	T. Nasdaq Tape AB	18.22%	6.38%	-11.84%***	18.17%	6.09%	12.08%***
	X. Nasdaq PSX	3.41%	1.29%	-2.11%***	3.42%	1.32%	-2.10%***
N/A	D. FINRA	N/A	N/A	N/A	N/A	N/A	N/A
N/A	M. CHX	0.02%	0.07%	0.05%**	0.02%	0.09%	0.08%**
N/A	V. IEX	2.96%	0.75%	-2.21%***	2.91%	0.73%	-2.18%***

Table 13 Regression of exchange operators' transaction fees around lit speed bump implementation

This table examines transaction fees consequence of lit speed bump implementation on the operators of stock exchanges during sample period Q1 2012 to Q2, 2017. Panel A/D, B/E & C/F report regression results for CBOE, ICE and NDAQ respectively. Lit speed bump_t is a dummy variable equals 1 in post-lit speed bump implementation period (Q4 2016 to Q2 2017), 0 otherwise. Dark speed bump_t is a dummy variable equals 1 in post-dark speed bump implementation period (Q1 2014 to Q2 2017), 0 otherwise. We report coefficient estimates from regression model (1):

$$Transaction\ fees\ _{i,t} = \beta_0 + \beta_1 Lit\ speed\ bump_t + \sum_i^{\delta}(control\ variables_{i,t}) + \varepsilon_{i,t}$$

and from regression model (2):

$$Transaction\ fees_{i,t} = \beta_0 + \beta_1 Lit\ speed\ bump_t + \beta_2 Dark\ speed\ bump_t + \sum_i^{\delta}(control\ variables_{i,t}) + \varepsilon_{i,t}$$

where Transaction $\text{fees}_{i,t}$ is one of the following variables for exchange operator i in quarter t: transaction fees, defined as transaction fees divided by revenue and transaction fees market share for exchange operator i in quarter t divided by the sum of transaction fees of CBOE, ICE and NDAQ. Lit speed bump_t is a dummy equals 1 post-lit speed bump implementation, 0 otherwise. Dark speed bump_t is a dummy equals 1 post-dark pool speed bump implementation, 0 otherwise. Control variables are as follows. Leverage is total liability divided by total asset. Size is log of total asset. Asset turnover is revenue divided by total assets. Operating cash flow is operating cash flow divided by total asset. The regressions are estimated with stock fixed effect. The asterisks ***, ** and * denote statistical significance of coefficient estimates at 1%, 5% and 10%.

	Panel A		Panel B		Panel C	
	Transaction fees (CBOE)		Transaction fees (ICE)		Transaction fees (NDAQ)	
VARIABLES	Model (1)	Model (2)	Model (1)	Model (2)	Model (1)	Model (2)
Lit speed bump_t	-0.108***	-0.110**	-0.0174	0.00894	0.0273**	0.0247*
	(0.00932)	(0.0129)	(0.736)	(0.515)	(0.0271)	(0.0881)
Dark speed bump_t		0.00595		0.384***		-0.00560
		(0.851)		(0.000946)		(0.717)
Leverage_{t-1}	0.671*	0.632	0.139	0.905*	-0.129	-0.128
	(0.0748)	(0.149)	(0.916)	(0.0501)	(0.228)	(0.245)
Size_{t-1}	-0.0298	-0.0323	0.0920	-0.306***	-0.204***	-0.179*
	(0.624)	(0.615)	(0.632)	(0.00880)	(0.00244)	(0.0668)
Asset Turnover_{t-1}	-0.179	-0.213	-1.572	-10.53	-4.059*	-3.371
	(0.529)	(0.538)	(0.949)	(0.148)	(0.0761)	(0.261)
Operating Cash_{t-1}	-0.0965	-0.0973	-5.138	7.570*	0.112	0.126
	(0.556)	(0.566)	(0.699)	(0.0933)	(0.821)	(0.806)
Constant	0.750*	0.787*	-0.796	2.711**	2.545***	2.280**
	(0.0730)	(0.0995)	(0.797)	(0.0316)	(0.000376)	(0.0263)
Observations	21	21	11	11	21	21
R-squared	0.545	0.546	0.164	0.958	0.856	0.857

	Panel D		Panel E		Panel F	
	Transaction fees market share (CBOE)		Transaction fees market share (ICE)		Transaction fees market share (NDAQ)	
VARIABLES	Model (1)	Model (2)	Model (1)	Model (2)	Model (1)	Model (2)
Lit speed bump$_t$	-0.120*	-0.118*	-0.0621	-0.0401	-0.0168	-0.0625
	(0.0642)	(0.0861)	(0.405)	(0.565)	(0.856)	(0.571)
Dark speed bump$_t$		-0.00669		0.322		-0.0984
		(0.899)		(0.225)		(0.431)
Leverage$_{t-1}$	-0.532	-0.488	0.668	1.310	-2.459***	-2.442**
	(0.376)	(0.491)	(0.721)	(0.476)	(0.00989)	(0.0117)
Size$_{t-1}$	0.0769	0.0797	0.547*	0.213	-0.0988	0.349
	(0.449)	(0.459)	(0.0834)	(0.551)	(0.832)	(0.636)
Asset Turnover$_{t-1}$	-0.521	-0.482	-10.69	-18.19	-41.21**	-29.13
	(0.277)	(0.405)	(0.756)	(0.577)	(0.0314)	(0.226)
Operating Cash$_{t-1}$	0.0767	0.0776	-10.76	-0.112	1.607	1.854
	(0.778)	(0.783)	(0.568)	(0.995)	(0.691)	(0.652)
Constant	0.183	0.141	-5.976	-3.039	4.441	-0.208
	(0.782)	(0.852)	(0.207)	(0.516)	(0.344)	(0.978)
Observations	21	21	11	11	21	21
R-squared	0.488	0.488	0.782	0.856	0.665	0.680

Table 14 Change in extant exchange operators' performance SEC approval of lit speed bump (together with IEX incorporation)
This table presents the change in extant exchange operators performance after SEC approval of lit speed bump (together with IEX incorporation). Panel A reports 5 quarterly performance metrics, ROA, Tobin's Q, net income, transaction fees revenue, EPS and short interest in Q1 2016 and Q1 2017 for exchange operators and the benchmarks, sourced from Bloomberg. Panel B reports S&P Financials and S&P 500 adjusted metrics.

Panel A: Percentage change of quarterly firm performance before (Q1 2016) and after (Q1 2017) introduction of speed bump in lit market

	ROA change%	Tobin's Q change%	Net Income change%	Transaction fees revenue Change%	EPS change%	Short Int change%
CBOE (Operates NSX, EDGA, EDGX, BYX, BZX)	-98%	-87%	-69%	-21%	-73%	22%
ICE(Operates NYSE MKT, NYSE, NYSE Arca)	36%	26%	36%	-4%	35%	-38%
NDAQ(Operates Nasdaq BX, Nasdaq, Nasdaq PSX)	21%	-1%	28%	0%	28%	-39%
Average	**-14%**	**-21%**	**-2%**	**-8%**	**-3%**	**-18%**
S&P Financials	-18%	-31%	38%	N.A.	28%	-30%
S&P 500	13%	7%	14%	N.A.	26%	-19%

Panel B: Difference in difference before and after speed bump for exchange operators adjusted by S&P 500 or S&P Financials index constituents

	ROA Diff-in-diff	Tobin's Q Diff-in-diff	Net Income Diff-in-diff	EPS Diff-in-diff	Short Int Diff-in-diff
CBOE (Operates NSX, EDGA, EDGX, BYX, BZX)	-80%	-56%	-107%	-101%	52%
ICE(Operates NYSE MKT, NYSE, NYSE Arca)	53%	57%	-2%	8%	-8%
NDAQ(Operates Nasdaq BX, Nasdaq, Nasdaq PSX)	39%	30%	-10%	0%	-9%
Average of Exchange adjusted by S&P Financials	**4%**	**10%**	**-40%**	**-31%**	**12%**
CBOE (Operates NSX, EDGA, EDGX, BYX, BZX)	-111%	-95%	-83%	-100%	41%
ICE(Operates NYSE MKT, NYSE, NYSE Arca)	22%	19%	22%	9%	-19%
NDAQ(Operates Nasdaq BX, Nasdaq, Nasdaq PSX)	8%	-8%	14%	1%	-20%
Average of Exchange adjusted by S&P 500	**-27%**	**-28%**	**-16%**	**-30%**	**1%**

Table 15 Regression of exchange operators' performance around lit speed bump implementation

This table examines economic consequence of lit speed bump implementation on the operators of stock exchanges during sample period Q1 2012 to Q2 2017. Panel A reports regression results for all exchange operators. Panel B, C & D report regression results for CBOE, ICE and NDAQ respectively. Lit speed bump_t is a dummy variable equals 1 in post-lit speed bump implementation period (Q4 2016 to Q2 2017), 0 otherwise. Dark speed bump_t is a dummy variable equals 1 in post-dark speed bump implementation period (Q1 2014 to Q2 2017), 0 otherwise. We report coefficient estimates from regression model (1):

$$Operators' \ performance_{i,t} = \beta_0 + \beta_1 Lit \ speed \ bump_t + \sum_i^{\delta}(control \ variables_{i,t}) + \varepsilon_{i,t}$$

and from regression model (2):

$$Operators' \ performance_{i,t} = \beta_0 + \beta_1 Lit \ speed \ bump_t + \beta_2 Dark \ speed \ bump_t + \sum_i^{\delta}(control \ variables_{i,t}) + \varepsilon_{i,t}$$

where Operators' $\text{performance}_{i,t}$ is one of the following variables in quarter t: ROA, defined as net income divided by total assets, Tobin's Q, defined as market value of common shares divided by total assets, net income and EPS. Lit speed bump_t is a dummy equals 1 post-lit speed bump implementation, 0 otherwise. Dark speed bump_t is a dummy equals 1 post-dark pool speed bump implementation, 0 otherwise. Control variables are as follows. Leverage is total liability divided by total asset. Size is log of total asset. Asset turnover is revenue divided by total assets. Operating cash flow is operating cash flow divided by total asset. The regressions are estimated with stock fixed effect. The asterisks ***, ** and * denote statistical significance of coefficient estimates at 1%, 5% and 10%.

Panel A: Regression for all exchange operators' financial performance adjusted by S&P Financials

	ROA		Tobin's Q		Net Income		EPS	
	Model (1)	Model (2)	Model (1)	Model (2)	Model (1)	Model (2)	Model (1)	Model (2)
Lit speed bump_t	-0.0169**	-0.0176**	0.000456	-0.944	-202.8***	-188.1***	-0.413***	-0.374**
	(0.0134)	(0.0484)	(0.999)	(0.242)	(4.43e-05)	(0.00285)	(0.00231)	(0.0325)
Dark speed bump_t		0.000843		1.117*		-17.34		-0.0468
		(0.900)		(0.0714)		(0.707)		(0.720)
Leverage_{t-1}		0.000843		1.117*		-17.34		-0.0468
		(0.900)		(0.0714)		(0.707)		(0.720)
Size_{t-1}	0.0301	0.0294	6.110*	5.125	-973.7***	-958.4***	-0.869	-0.827
	(0.428)	(0.449)	(0.0907)	(0.151)	(0.000434)	(0.000662)	(0.243)	(0.275)
Asset Turnover_{t-1}	-0.00108	-0.00220	0.900	-0.581	16.69	39.67	0.0351	0.0971
	(0.901)	(0.860)	(0.276)	(0.611)	(0.781)	(0.645)	(0.837)	(0.690)
Operating Cash_{t-1}	0.253***	0.245**	35.53***	24.97***	-238.5	-74.79	-0.304	0.138
	(0.000721)	(0.0127)	(1.80e-06)	(0.00572)	(0.626)	(0.909)	(0.826)	(0.941)
Constant	0.0138	0.0114	2.949*	-0.237	-607.9***	-558.5***	-0.419	-0.285
	(0.413)	(0.656)	(0.0658)	(0.919)	(2.27e-06)	(0.00234)	(0.204)	(0.566)
Observations	63	63	63	63	63	63	63	63
R-squared	0.916	0.916	0.921	0.926	0.563	0.564	0.201	0.203

Panel B: Regression for CBOE financial performance adjusted by S&P Financials

	ROA		Tobin's Q		Net Income		EPS	
	Model (1)	Model (2)	Model (1)	Model (2)	Model (1)	Model (2)	Model (1)	Model (2)
Lit speed bump$_t$	-0.0572***	-0.0580**	-1.029	-5.226*	-282.8***	-201.7	-0.449***	-0.269
	(0.00471)	(0.0374)	(0.637)	(0.0725)	(0.00368)	(0.105)	(0.00711)	(0.199)
Dark speed bump$_t$		0.000740		3.810**		-73.60		-0.163
		(0.964)		(0.0445)		(0.341)		(0.223)
All controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Panel C: Regression for ICE financial performance adjusted by S&P Financials

	ROA		Tobin's Q		Net Income		EPS	
	Model (1)	Model (2)	Model (1)	Model (2)	Model (1)	Model (2)	Model (1)	Model (2)
Lit speed bump$_t$	-0.00510	-0.00466	0.123	0.00443	-124.7	8.602	-0.687	-0.540
	(0.206)	(0.265)	(0.534)	(0.967)	(0.712)	(0.977)	(0.214)	(0.312)
Dark speed bump$_t$		0.00239		-0.644***		725.9**		0.801
		(0.559)		(2.79e-05)		(0.0244)		(0.141)
All controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Panel D: Regression for NDAQ financial performance adjusted by S&P Financials

	ROA		Tobin's Q		Net Income		EPS	
	Model (1)	Model (2)	Model (1)	Model (2)	Model (1)	Model (2)	Model (1)	Model (2)
Lit speed bump$_t$	-0.00648	0.00246	-0.0101	-0.0804	-26.86	129.5	-0.550	0.205
	(0.579)	(0.868)	(0.942)	(0.657)	(0.897)	(0.626)	(0.562)	(0.865)
Dark speed bump$_t$		-0.00493		0.0387		-86.11		-0.416
		(0.275)		(0.843)		(0.299)		(0.222)
All controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table 16 Market reaction to SEC approval of lit speed bump (together with IEX incorporation) and extant exchange operators' performance

This table presents market reaction to SEC approval of lit speed bump (together with IEX incorporation) and the change in extant exchange operators performance. Panel A reports the CARs in different event windows around the announcement date, June 17, 2016. Abnormal returns are calculated with market-adjusted model for the 3 operators CBOE, ICE and NDAQ that own the stock exchanges. We use two benchmarks, S&P Financials and S&P 500 as market indices. CARs reported below are for individual operators as well as the average across the 3 operators. The asterisks ***, ** and * denote statistical significance at 1%, 5% and 10%. Panel B reports 5 quarterly performance metrics, ROA, Tobin's Q, net income, transaction fees revenue, EPS and short interest in Q1 2016 and Q1 2017 for exchange operators and the benchmarks, sourced from Bloomberg. Panel C reports S&P Financials and S&P 500 adjusted metrics.

Panel A CARs%		S&P Financials as benchmark	S&P 500 as benchmark
CAR(-1,+1)	CBOE	-2.72	-1.98
	ICE	-2.50	-1.75
	NDAQ	-3.46	-2.71
	Overall	-2.89***	-2.14**
CAR(-2,+2)	CBOE	-4.40	-3.19
	ICE	-4.17	-2.96
	NDAQ	-4.39	-3.18
	Overall	-4.32***	-3.11***
CAR (-3,+3)	CBOE	-1.14	-1.13
	ICE	-3.17	-3.16
	NDAQ	-2.98	-2.97
	Overall	-2.43*	-2.42*

Table 17 Regression of short interest in exchange operators' own stock around lit speed bump implementation

This table examines short interest consequence of lit speed bump implementation on the operators of stock exchanges during sample period Q1 2012 to Q2, 2017. Panel A, B & C report regression results for CBOE, ICE and NDAQ respectively. Lit speed bump_t is a dummy variable equals 1 in post-lit speed bump implementation period (Q4 2016 to Q2 2017), 0 otherwise. Dark speed bump_t is a dummy variable equals 1 in post-dark speed bump implementation period (Q1 2014 to Q2 2017), 0 otherwise. We report coefficient estimates from regression model (1):

$$Short\ interest\ _{i,t} = \beta_0 + \beta_1 Lit\ speed\ bump_t + \sum_{i}^{\delta}(control\ variables_{i,t}) + \varepsilon_{i,t}$$

and from regression model (2):

$$Short\ interest\ _{i,t} = \beta_0 + \beta_1 Lit\ speed\ bump_t + \beta_2\ Dark\ speed\ bump_t + \sum_{i}^{\delta}(control\ variables_{i,t}) + \varepsilon_{i,t}$$

where $\text{Short interest}_{i,t}$ is defined as the mean of short position for exchange operator i in quarter t. Lit speed bump_t is a dummy equals 1 post-lit speed bump implementation, 0 otherwise. Dark speed bump_t is a dummy equals 1 post-lit speed bump implementation, 0 otherwise. Control variables are as follows. Leverage is total liability divided by total asset. Size is log of total asset. Asset turnover is revenue divided by total assets. Operating cash flow is operating cash flow divided by total asset. The regressions are estimated with stock fixed effect. The asterisks ***, ** and * denote statistical significance of coefficient estimates at 1%, 5% and 10%.

	Panel A		Panel B		Panel C	
	Short interest (CBOE)		Short interest (ICE)		Short interest (NDAQ)	
VARIABLES	Model (1)	Model (2)	Model (1)	Model (2)	Model (1)	Model (2)
Lit speed bump_t	3.960***	3.581***	1.126	-1.135	-0.763	0.594
	(1.16e-05)	(4.71e-06)	(0.934)	(0.934)	(0.411)	(0.494)
Dark speed bump_t		1.295***		-38.11		2.921***
		(0.00626)		(0.346)		(0.00838)
Leverage_{t-1}	6.990	-1.380	99.62	-123.2	-4.165	-4.644
	(0.260)	(0.801)	(0.673)	(0.711)	(0.622)	(0.495)
Size_{t-1}	1.621	1.069	-8.612	16.09	12.40**	-0.888
	(0.130)	(0.210)	(0.823)	(0.729)	(0.0156)	(0.878)
$\text{Asset Turnover}_{t-1}$	17.93***	10.52**	-1,361	-1,455	355.2*	-3.450
	(0.00177)	(0.0304)	(0.690)	(0.671)	(0.0572)	(0.985)
$\text{Operating Cash}_{t-1}$	2.486	2.312	123.8	-183.6	16.80	9.460
	(0.378)	(0.300)	(0.958)	(0.938)	(0.676)	(0.769)
Constant	-23.11***	-15.07**	34.23	-22.03	-132.2**	5.797
	(0.00336)	(0.0208)	(0.955)	(0.971)	(0.0104)	(0.921)
Observations	21	21	21	21	21	21
R-squared	0.869	0.924	0.342	0.384	0.509	0.706

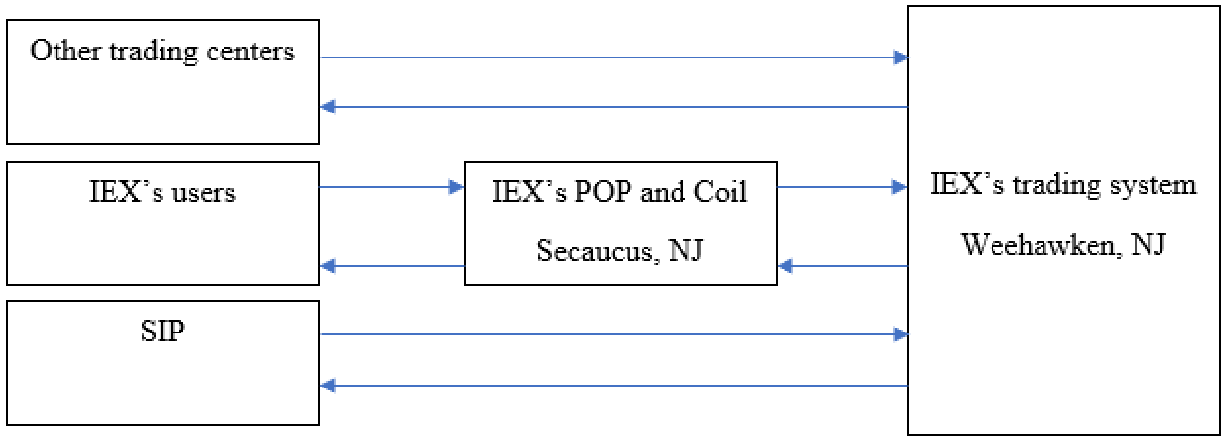

Figure 1. IEX speed bump
This figure depicts how IEX's speed bump works. SIP stands for Securities Information Processor. POP is the point of presence in Secaucus, NJ. Coil is the 38-mile optic fiber-coil in Secaucus, NJ.

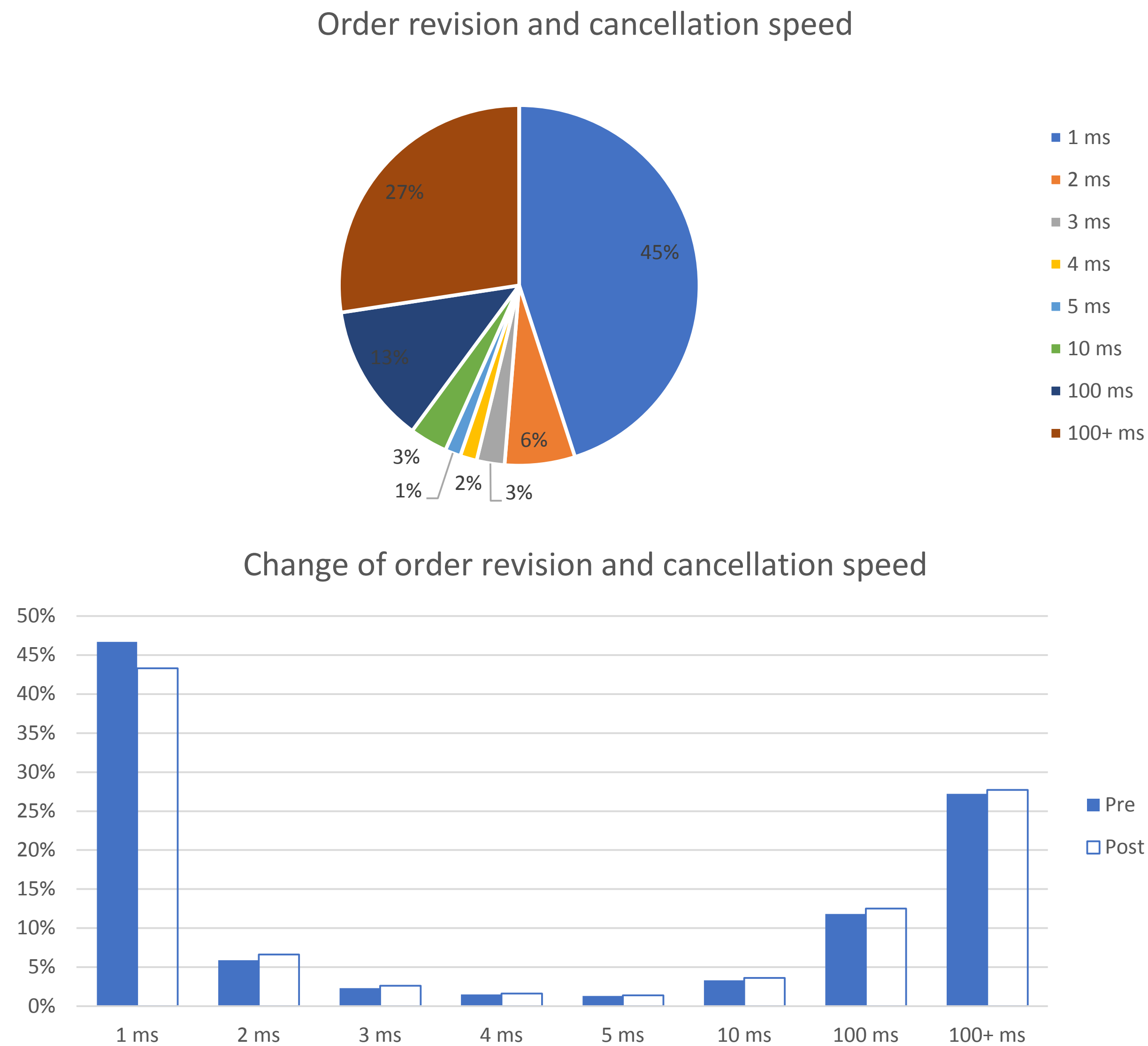

Figure 2: Order revision and cancellation speed
The upper part reports the proportion of each time bucket based on reaction (revision or cancellation) speed. The lower part reports the proportion of each time bucket based on reaction speed pre-lit speed bump implementation and post-lit speed bump implementation.

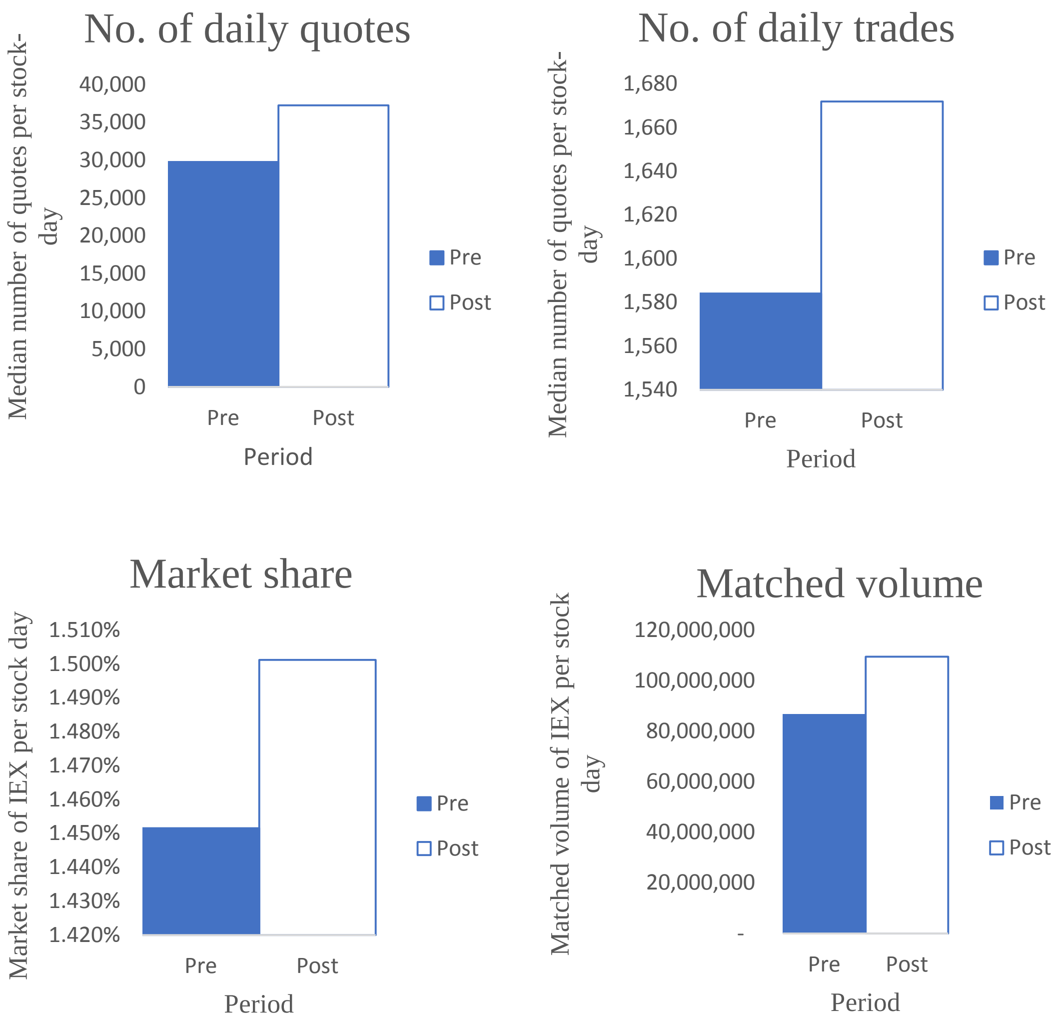

Figure 3: IEX market activity and market share around the period when it became a stock exchange
The upper part reports the median number of quote submissions and trade submissions around the implementation of lit speed bump, and the lower part reports the median value of IEX's market share and matched volume around the implementation of lit speed bump. The horizontal axes reflect the time period around the implementation of lit speed bump. The vertical axes reflect number of quotes, number of trades, market share and matched volume respectively.

APPENDIX

A 1 Summary of intentional delays petitioned by stock exchanges

This table summarizes the intentional delays petitioned by stock exchanges in U.S. and Canada. It reports the details of U.S. stock exchanges including IEX, NYSE MKT, Nasdaq and Chicago that petitioned for speed bumps. The summary is based on SEC (Securities and Exchange Commission)'s approval notices.

Intentional delay name	**Pop/Coil delay**	**Delay Mechanism**	**ELP**	**N/A**	**LEAD**
Latency length	350 microseconds	350 microseconds	1 second	N/A	350 microseconds
Orders subject to the latency	Incoming/Outgoing	Inbound/Outbound	Designated retail orders	N/A	Incoming
Solution	Hardware	Software	Compliance/Monitor	N/A	Software
Petition date	21-Aug-15	27-Jan-17	17-Nov-16	N/A	10-Feb-17
Approval date	17-Jun-16	16-May-17	7-Jul-17	N/A	19-Oct-17
Implementation date	19-Aug-16	24-Jul-17	2nd half, 2018	N/A	Halted on Oct 25, 2017
Stock Exchange	IEX	NYSE MKT	Nasdaq	None	Chicago
Status	Privately held	Publicly listed	Publicly listed	Publicly listed	Privately held
Owner/Operator	N/A	ICE	NDAQ	CBOE	N/A

A 2 Hypothesis flowchart