Tick Size Pilot Plan and Market Quality[1]

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January 31 2018

Abstract

This paper examines the effects of the Tick Size Pilot Plan on average stock market quality. We compare changes in market quality, as measured by spreads, quoted depth, trading volume, volatility, and price efficiency, between the Test and Control Groups. Overall, we find that on average, relative to stocks in the Control Group, market quality deteriorates for stocks in the Test Groups. Specifically, we find that stocks in the Test Groups experience an increase in spreads and volatility and a decrease in price efficiency, relative to stocks in the Control Group. We find that displayed depth at the best quotes increases for all Test Groups. However, when we compare the displayed depth at the best quotes to the total displayed depth within five cents of the best quotes prior to the Pilot, we find that the displayed depth only increases for stocks in the Test Group subject to the trade-at rule. We find that displayed depth within fifteen cents of the best displayed quotes increases for all Test Groups. However, this increase in depth does not appear to lower the transaction costs of large orders, which also increase when the tick size widens. We find that the deterioration in market quality appears to be greater for stocks that had average quoted spreads less than the increased tick size (i.e., less than five cents) during the pre-Pilot period. Our evidence suggests that these findings are mainly driven by the widening of quoting increments as opposed to imposing a trading increment or a trade-at rule, as we only find a few significant differences between the different Test Groups (e.g. the Test Group subject to the trade-at rule).

[1] This paper uses Pilot data available as of September 2017. Pilot data provided by the SROs has and might continue to change as Self-Regulatory Organizations update or correct historical data. We do not anticipate that additional changes in Pilot data would affect our conclusions because our results from existing Pilot data are consistent with our results from data that will not change (NYSE's Daily Trade and Quote (TAQ) data and data from the Market Information Data Analytics System (MIDAS)). See infra Section 4.

[2] The Securities and Exchange Commission disclaims responsibility for any private publication or statement of any SEC employee or Commissioner. This white paper expresses the authors' views and does not necessarily reflect those of the Commission, the Commissioners, or other members of the staff. This white paper was prepared as a part of the Division of Economic and Risk Analysis (DERA) White Paper series.

1. Introduction

On August 25, 2014, FINRA and the national securities exchanges proposed, and on May 6, 2015, the SEC approved, the Tick Size Pilot Program (the "Pilot").[3,4] The Pilot, among other things, widens the minimum quoting and trading increment for certain small capitalization stocks (i.e., increases the tick size).[5] The Pilot is designed to, among other things, permit researchers to evaluate how a wider tick size would impact the trading, liquidity, and market quality of stocks of smaller capitalization companies. This paper uses the controlled experiment setting of the Pilot to examine the effects of an increase in the tick size on the market quality for smaller capitalization, less actively traded stocks.

Market quality is a broad concept, which encompasses both price efficiency and market liquidity. Price efficiency refers to the degree to which stock prices reflect all available information. For instance, price efficiency is often measured in terms of how long it takes for information to be compounded into returns, or how much prices deviate from fundamentals. Market liquidity refers to the degree to which an investor can buy or sell an asset quickly without incurring large transactions costs or exerting a material effect on the asset's price.[6] Two dimensions of market liquidity that are commonly discussed are spreads and depth. Spread refers to the difference between the price at which an asset can be bought and sold and represents the round trip transactions cost of the purchase and sale of the asset. Depth refers to how much of an asset can be bought or sold without dramatically moving the price. Two other measures that are often related to market liquidity are trading volume and volatility. Larger trading volume is an indicator of greater liquidity, because more people are willing to buy and sell an asset, which means it can be traded faster without materially impacting the

[3] See Notice of Filing of Proposed National Market System Plan to Implement a Tick Size Pilot Program On a One-Year Pilot Basis; Joint Industry Plan; BATS Exchange, Inc., BATS Y-Exchange, Inc., Chicago Stock Exchange, Inc., EDGA Exchange, Inc., EDGX Exchange, Inc., Financial Industry Regulatory Authority, Inc., NASDAQ OMX BX, Inc., NASDAQ OMX PHLX LLC, The Nasdaq Stock Market LLC, New York Stock Exchange LLC, NYSE MKT LLC, and NYSE Arca, Inc.; Release No. 73511; File No. 4-657 (November 3, 2014).

[4] See Order Approving the National Market System Plan to Implement a Tick Size Pilot Program ("Approval Order") by BATS Exchange, Inc., BATS Y-Exchange, Inc., Chicago Stock Exchange, Inc., EDGA Exchange, Inc., EDGX Exchange, Inc., Financial Industry Regulatory Authority, Inc., NASDAQ OMX BX, Inc., NASDAQ OMX PHLX LLC, The Nasdaq Stock Market LLC, New York Stock Exchange LLC, NYSE MKT LLC, and NYSE Arca, Inc., as Modified by the Commission, For a Two-Year Period, Securities Exchange Act Release No. 74892 (May 6, 2015).

[5] See Order Directing the Exchanges and the Financial Industry Regulatory Authority To Submit a Tick Size Pilot Plan, Release No. 34-72460 (June 24, 2014) https://www.sec.gov/rules/other/2014/34-72460.pdf.

[6] Transactions costs are the expenses incurred in buying or selling a stock.

price. Greater volatility may indicate lower liquidity, because prices tend to move more when there is less depth to execute large orders.

Academic researchers have previously investigated the effects on market quality of the tick size reduction caused by decimalization and the change from one-eighths to one-sixteenths.[7,8] The majority of these studies (see, e.g., Bessembinder, 2003; Bacidore et al., 2003; Chordia et al., 2008; Zhao and Chung, 2006) suggest that the tick size reduction led to better market quality, including lower transactions costs and greater price efficiency. However, some traders and lawmakers have argued that decimalization reduced the economic incentives for market makers or investment bankers to provide liquidity for small-cap stocks, leading to inferior market quality. For example, during the SEC Decimalization Roundtable some participants argued that decimalization may have contributed to a reduction in liquidity for small cap stocks, because the smaller tick size decreased the profits market makers could earn, which reduced their incentive to supply liquidity in less actively traded stocks.[9] In the Approval Order, the SEC stated that the effect of wider tick sizes for small capitalization stocks on trading, liquidity, and market quality is not clear and the Tick Size Pilot would provide data to analyze any such effects.[10] This white paper empirically examines the effects of the Pilot on average market quality. We leave for future research an in-depth analysis of

[7] Decimalization occurred in 2001 and reduced the tick size for all US stock markets from one-sixteenth (1/16th) of one dollar to one cent. See Order Directing the Exchanges and the National Association of Securities Dealers, Inc. To Submit a Decimalization Implementation Plan Pursuant to Section 11A(a)(3)(B) of the Securities Exchange Act of 1934 65 Fed. Reg. 5003, 5004 (Feb. 2, 2000).

[8] In 1997 the New York Stock Exchange (NYSE), NASDAQ, and the American Stock Exchange (AMEX) reduced their tick sizes from one-eighth (1/8th) of one dollar to one-sixteenth (1/16th) of one dollar. See Self-Regulatory Organizations; New York Stock Exchange, Inc.; Order Granting Approval to Proposed Rule Change Relating to Trading Differentials for Equity Securities, 62 Fed. Reg. 42847 (Aug. 8, 1997). Also see Self-Regulatory Organizations; National Association of Securities Dealers, Inc.; Order Granting Approval to Proposed Rule Change To Decrease the Minimum Quotation Increment for Certain Securities Listed and Traded on The NASDAQ Stock Market to 1/16th of $1.00, 62 Fed. Reg. 30363 (June 3, 1997). Also see Self-Regulatory Organizations; American Stock Exchange, Inc.; Order Granting Approval to Proposed Rule Change Relating to Trading in One Sixteenth of a Dollar, 62 Fed. Reg. 25682 (May 9, 1997).

[9] On February 5, 2013, the SEC hosted a Decimalization Roundtable to discuss the impact of tick sizes on small and mid-sized companies, market professionals, investors, and U.S. securities markets. See https://www.sec.gov/spotlight/decimalization.shtml.

[10] See Approval Order, supra note 3. For a comprehensive review on the history of the Tick Size Pilot, including the Decimalization Roundtable, SEC Staff Report to Congress on Decimalization, and the IPO Task Force see the Background section of the Order Directing the Exchanges and the Financial Industry Regulatory Authority To Submit a Tick Size Pilot Plan, supra note 4.

variation in market quality changes (i.e., how market quality changes vary across different types of stocks), as well as market maker profitability.

Below we summarize our overall findings regarding the effects of the Pilot on market quality.

- An increase in tick size appears to cause deterioration in market quality, on average. Specifically, we find that, relative to stocks in the Control Group, stocks in the Test Groups experience an increase in spreads and volatility and a decrease in price efficiency.

- Our evidence suggests that these findings are mainly driven by the widening of quoting increments as opposed to imposing a trading increment or a trade-at rule, as we find few statistically significant differences in the changes to market quality between the three Test Groups.

- We find that displayed depth at the best quotes increases in all Test Groups, relative to the Control Group, but the total displayed depth within five cents of the best quotes only increases in the Test Group subject to the trade-at rule.

- We also find an increase in cumulative displayed depth beyond the best quotes. However, this increase in depth does not appear to improve the transactions costs of large orders, which also increase when the tick size widens.

- We find the deterioration in market quality caused by the tick size increase is greater in subsamples in which the average pre-Pilot quoted spreads are smaller than five cents. This could indicate that the tick size increase causes market quality to deteriorate for stocks in which the natural spread is smaller than the new tick size.[11]

2. Review of Related Tick Size Studies

Numerous studies have examined the effects of tick size changes on market quality. Reviewing these studies helps us understand if the results we observe from the Pilot are consistent with the effects of prior tick size changes. This section reviews prior and contemporaneous studies of tick size changes and summarizes their findings regarding the effects of tick size changes on market liquidity and price efficiency. The review includes other academic and industry studies that examine the Pilot.

2.1 Review of effects of tick size changes on market liquidity

[11] Natural spread refers to what the equilibrium bid ask spread would be for a stock in a market without a minimum price increment.

A number of studies have examined how the tick size reductions due to decimalization and the change in minimum quotes from one-eighths to one-sixteenths affected the different dimensions of market liquidity.[12,13] Most studies found that the reduction in tick size reduced spreads and decreased depth at the best quotes (see Bessembinder, 2003; Chakravarty, Harris, and Wood, 2001; Chakravarty, Wood, and Van Ness, 2004; Ronen and Weaver, 2001; Bollen and Whaley, 1998; and Van Ness et al., 2000).[14],[15] The decline in spreads indicates that a reduction in tick size reduced the transactions costs for small orders.

However, since depth is also reduced, it is unclear if tick size reductions altered the transactions costs of larger orders. A number of studies have examined this issue and found mixed results. Some studies find that transactions costs for larger orders decline after decimalization (see Bacidore, Battalio, and Jennings, 2003; Chakravarty, Panchapagesan, and Wood, 2005; and Werner, 2003). While other studies (see Chakravarty, Harris, and Wood, 2001) find that the transactions costs for large trades did not change following decimalization.

Trading volume is often used as an indirect measure of realized market liquidity, since investors may prefer to trade more in liquid stocks. Existing studies provide mixed evidence of how a change in tick size affects trading volume. Chou and Chung (2006) find that ETFs experienced an increase in trading volume following decimalization. Ahn, Cao, and Choe (1996) find that trading volume was unchanged when the tick size for AMEX-listed low-priced stocks was reduced from one-eighths to one-sixteenths in September 1992.

Stock return volatility is often used as an indirect measure of market liquidity. Higher volatility is often associated with lower liquidity, because prices tend to move more when there is less liquidity to execute large orders. A number of studies have looked at how tick size change affects volatility and most have found that a reduction in tick size decreases

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[12] See supra notes 7 and 8 for descriptions of decimalization and the switch from one-eighths to one-sixteenths minimum quotes.

[13] One key difference between the tick size change in the Pilot and the tick size changes during decimalization and the change in minimum quotes from one-eighths to one-sixteenths is the tick size change during the Pilot only applies to a subset of small-cap stocks while the other tick size changes apply to all stocks.

[14] Bessembinder (2003) also examined how spreads changed in different market capitalization groups around decimalization. He found a statistically significant decline in spreads following decimalization across all NYSE and Nasdaq market cap groups except Nasdaq small cap stocks, where he found a statistically insignificant decrease in quoted and effective spreads.

[15] Most studies found that depth at the best quotes decreased following decimalization. However, Bacidore, Battalio, and Jennings (2003) found that total depth within 15 cents of the quote midpoint did not significantly change following decimalization.

volatility (see Bessembinder, 2003; Bessembinder and Wu, 2005; Chakravarty, Wood, and Van Ness, 2004; and Ronen and Weaver, 2001).[16]

Overall, most of these findings are consistent with the argument that the tick size reductions due to decimalization and the change in minimum quotes from one-eighths to one-sixteenths are associated with an increase in market liquidity. However, during the SEC Decimalization Roundtable, some participants argued that decimalization may have reduced liquidity for small-cap stocks, because market makers earn lower profits from smaller spreads, and therefore have less incentive to provide liquidity.[17]

2.2 Review of effects of tick size changes on price efficiency

Studies have also examined how changes in tick size affect the efficiency of prices. Chordia, Roll, and Subrahmanyam (2008) examined a reduction in the minimum tick size in 1997 from one-eighths to one-sixteenths and found that it improved price efficiency and allowed new information to be incorporated more quickly into prices. Kurov (2008) examined a 2006 reduction in the minimum tick size in the E-mini futures market and also found that this reduction improved price efficiency.

However, during the SEC Decimalization Roundtable, some participants indicated that decimalization could have indirectly decreased price efficiency in small-cap stocks.[18] Some participants argued that decimalization reduced the revenue market makers and investment banks earned from smaller capitalization stocks, which caused them to reduce equity analyst coverage in smaller cap stocks. The reduction in analyst coverage may have reduced the available information about these stocks, and caused prices to drift from fundamentals.

2.3 Review of other Tick Size Pilot studies

Contemporary academic studies also examined the effects of the Pilot on market quality and found that the increase in tick size reduced certain dimensions of market quality for stocks in the Test Groups (see Griffith and Roseman, 2017; Hansen et al., 2017; Lin et. al., 2017; and Rindi and Werner, 2017). Specifically, most of these studies found that spreads and volatility increased and trading volume decreased for stocks in the Test Groups.[19] However, Hansen et al. (2017) also found that depth at the best quotes increased for stocks in the Test Groups.

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[16] Chakravarty, Wood, and Van Ness (2004) found that volatility increased for NYSE stocks shortly after decimalization was implemented, but found that it declined over the longer term.

[17] See supra note 9.

[18] See supra note 9.

[19] A related study (Comerton-Forde, Gregoire, and Zhong, 2017) examines the impact of inverted fee models on market quality, noting that inverted venue market share increased due to the Tick Size Pilot Program. They find

In addition, some industry practitioners have conducted studies to evaluate the impact of the Pilot on market quality. The results of these studies agreed with the academic studies and found that spreads, depth at the best quotes, and return volatilities increased for stocks in the Test Groups (see Clearpool Review, 2017; J.P. Morgan, 2017; Convergex, 2017; Ruane and Pearson, 2017).[20]

3. Description of the Tick Size Pilot Program

This section provides an overview of the Tick Size Pilot Program and discusses the quoting and trading characteristics of each of the three Test Groups.

In June 2014, the SEC directed FINRA and the national securities exchanges to act jointly in developing and filing a plan to implement a pilot program that, among other things, would widen the quoting and trading increment for certain small capitalization stocks.[21] On August 25, 2014, FINRA and the national securities exchanges proposed, and on May 6, 2015, the SEC approved, the Tick Size Pilot.[22,23] As stated in the Approval Order, "the Tick Size Pilot is therefore, by design, an objective, data-driven test that is designed to evaluate how a wider tick size would impact trading, liquidity, and market quality of stocks of smaller capitalization companies."[24] The Pilot began to be phased-in on October 3, 2016, and includes only common stocks that satisfy all of the following conditions:

1. Market Capitalization (Shares Outstanding times Closing Price) of $3 billion or less on the last day of the Measurement Period; [25]
2. Consolidated Average Daily Volume ("CADV") during the Measurement Period of one million shares or less, where the CADV is calculated by adding the single counted share volume of all reported transactions in the Pilot Stock during the Measurement

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that higher inverted venue share improved pricing efficiency, increased liquidity, and decreased volatility. Their findings suggest that the finer pricing grid provided by inverted venues encourages competition between liquidity providers and improves market quality.

[20] A number of the industry studies also find that the off-exchange market share of trading volume has seen a moderate increase in Test Groups 1 & 2, and a decrease in Test Group 3 (see Clearpool Review, 2017; J.P. Morgan, 2017; and Ruane and Pearson, 2017).

[21] See supra note 5.

[22] See supra note 3.

[23] See supra note 4.

[24] See supra note4.

[25] "Measurement Period" means the U.S. trading days during the three calendar-month period ending at least 30 days prior to the effective date of the Pilot Period.

Period and dividing by the total number of U.S. trading days during the Measurement Period;

3. Closing Price of at least $2.00 on the last day of the Measurement Period and Closing Price on every U.S. trading day during the Measurement Period that is not less than $1.50;

4. A Measurement Period VWAP of at least $2.00, where the Measurement Period VWAP is determined by calculating the VWAP for each U.S. trading day during the Measurement Period, summing the daily VWAP across the Measurement Period, and dividing the total number of U.S. trading days during the Measurement Period.

The groups to which eligible stocks were assigned were first published on September 6, 2016, and these groups are updated daily by FINRA.[26] The list of the Pilot Stocks indicates that the Pilot covers approximately 2,400 stocks.[27]

These 2,400 stocks are stratified into four groups: one Control Group and three Test Groups. Stocks in the Control Group quote and trade at their pre-Pilot tick size increment. Stocks in Test Group 1 quote in $0.05 increments and trade at their pre-Pilot tick size increment. Stocks in Test Group 2 quote and trade in $0.05 minimum increments, but allow certain exemptions for midpoint executions, retail investor executions, and negotiated trades. Stocks in Test Group 3 adhere to the requirements of Test Group 2, but are also subject to a "trade-at" requirement, which prevents price matching by trading centers that are not already displaying a quotation at that price. There are exceptions to the trade-at requirement that are similar to the exceptions provided in Rule 611. We summarize this information in the following table:

Groups	**Quote Increment**	**Trade Increment**	**Inclusion of Trade-at Requirement**
Control Group	Status quo	Status quo	No
Test Group 1	$0.05	Status quo	No
Test Group 2	$0.05	$0.05	No
Test Group 3	$0.05	$0.05	Yes

[26] See http://www.finra.org/industry/test-group-assignments.

[27] Please refer to https://www.nasdaqtrader.com/Trader.aspx?id=TickPilot and http://www.finra.org/industry/tick-size-pilot-program for the list of Pilot Stocks and some related information.

The stocks in each of the Test and Control Groups were selected using a stratified sampling approach that was designed to ensure each group was representative of small-cap stocks.[28] The different Test Groups provide a way to measure the incremental effects of the trade-at requirement and changes in the trading increments on top of changes in the quoting increments, but do not allow for separate examination of the effects of the trade-at restriction or increased trading increments independently of the effects of the increased quoting increments.

4. Data Sources, Variable Descriptions, and Summary Statistics

This section provides a brief overview of our sample and the data sources we use for our analysis. It also defines and provides summary statistics for the measures we use to assess market efficiency and market liquidity.

The sample used in our study includes the approximately 2,400 stocks in the Control Group and Test Groups of the Pilot. Given that the Pilot came into effect following a staggered implementation schedule during October 2016 (see Appendix A), we define the four months prior to October 2016 (i.e., June 2016 - September 2016) as the pre-Pilot period and the four months after October 2016 (i.e., November 2016 - February 2017) as the Pilot period in our univariate tests and difference-in-differences analysis. In other words, our sample period is between June 2016 and February 2017 and is equally made up of two four-month sub-periods before and after the Pilot implementation in October 2016.[29]

In this study, we use data provided by the SROs to the SEC under the Pilot and publicly available data from the Market Information Data Analytics System (MIDAS), the NYSE's Daily Trade and Quote (TAQ) database, the Center for Research in Security Prices (CRSP) database, and the Chicago Board Options Exchange (CBOE) website. The Pilot data includes data on market quality statistics for different order types and data on market and marketable limit orders, which is collected by the SROs and provided to the SEC on a monthly basis. The MIDAS database provides information on the displayed limit order book for each of the national securities exchanges. The TAQ database provides intraday transaction and quotation

[28] The Pilot Stocks are placed into three Test Groups by means of a stratified random sampling process. The Pilot Stocks are stratified based on price, market capitalization, and trading volume, and each of these three strata are further subdivided into low, medium, or high strata. An equal number of stocks from each of the sub-strata are randomly assigned to each of the Test Groups. The Pilot Stocks not placed into the three Test Groups constitute the Control Group. Please refer to page 4 of Tick Size Pilot Plan transmittal letter prepared by the NYSE on behalf of participants of the Tick Size Pilot Plan (https://www.sec.gov/divisions/marketreg/tick-size-pilot-plan-transmittal-letter.pdf). Similar discussions can be found on page 13 of "Plan to implement a Tick Size Pilot Program". https://www.sec.gov/rules/sro/nms/2015/34-74892-exa.pdf

[29] We do not include October 2016 in our analysis due to the staggered phase-in of the Tick Size Pilot.

data for all issues traded on the national securities exchanges. The CRSP database provides information on stock characteristics as well as daily trading volume and prices. The CBOE website provides data on the VIX volatility index. We use this data to construct the market quality measures and control variables used in our analysis. When we construct our measures, we apply filters to some of the data to reduce the influence of data errors and extreme observations. Appendix B discusses our data filtering.

There is no definitive measure of market liquidity or price efficiency. Therefore, in our analysis we construct various market quality measures to examine how the Pilot affects market liquidity and price efficiency. We construct a number of market liquidity measures to examine changes in different dimensions of liquidity, including: spreads, depth, trading volume, and stock return volatility. We also construct a number of measures to examine changes in price efficiency.

For some of our spread measures, we construct two versions of the measure, one based on the TAQ data and one based on the Pilot data. A limitation of the TAQ data is that it only contains information on trades and not orders. This means that orders that execute across multiple trades would appear as separate transactions in the TAQ data, so spread measures could not be calculated for the entire order. Moreover, a change in tick size could alter the size of orders that traders submit. One advantage of the Pilot data is that it contains information on orders, so we are able to calculate spread measures for the entire order and also examine how the tick size change affects orders of different sizes.

Specifically, we construct the following measures of liquidity:

- *Rel Q-spread (Pilot data):* The relative quoted spread is the difference between the National Best Offer (NBO) and the National Best Bid (NBB), divided by the daily volume-weighted average price (VWAP) based on the midpoint of the NBB and NBO (NBBO midquote).[30] It can be viewed as a measure of the round trip cost of buying and selling the stock using market orders. A higher value indicates larger transactions costs for small orders. This measure is calculated from the Pilot data and is a share-weighted average based on the NBB and NBO observed at the time an order is submitted.

- *Rel Q-spread (TAQ data):* This measure of relative quoted spread is computed from TAQ. It is calculated as the time-weighted daily average of the difference between the log NBO and log NBB.

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[30] National Best Bid and National Best Offer are defined under Rule 600(b)(42) of Regulation NMS under the Exchange Act.

- *Rel E-spread (Pilot data):* The relative effective spread is double the difference between the price paid for a stock and the NBBO midquote, divided by the daily volume-weighted average price (VWAP) based on trade prices. It is a measure of the transaction price an investor actually pays and captures any price improvement the investor might receive beyond the displayed quotes. A higher value indicates larger transactions costs. This measure is calculated from the Pilot data. The NBBO midquote is calculated based on the NBB and NBO observed when an order was submitted and the measure is a share-weighted average of the prices at which the order was executed.[31]

- *Rel E-spread (TAQ data)*: This measure of relative effective spread is computed from TAQ. It is calculated as the share weighted daily average of the absolute value of double the difference between the log trade price and the log NBBO midquote before the trade took place.

- *Rel R-spread (TAQ data):* The relative realized spread is the signed difference between the log price paid for a transaction and the log NBBO midquote observed five minutes after the execution takes place.[32] The realized spread is a measure of the revenue a market maker earns for supplying liquidity in a transaction. A higher value indicates the market maker earns more revenue from supplying liquidity. The realized spread measure is calculated from the share-weighted daily average realized spreads of the trades that occur during the day.

- *Rel Price Impact (TAQ data):* The relative price impact is the signed difference between the log NBBO midquote at the time right before the trade took place and the log NBBO midquote observed five minutes after the trade took place.[33] The price impact is commonly viewed as a measure of the cost of adverse selection that a market maker faces for supplying liquidity to informed traders.[34] A higher value indicates that the adverse selection cost a market maker faces is larger and is viewed as a

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[31] The effective spread is calculated by multiplying the difference between the transaction price and the midpoint by the sign of the order. A buy order has a sign of 1 and a sell order has a sign of -1.

[32] The realized spread is calculated by multiplying the difference between the transaction price and the midpoint by the sign of the trade. A trade initiated by a market buy order has a sign of 1 and a trade initiated by a market sell order has a sign of -1.

[33] The price impact is calculated by multiplying the difference between the midpoints by the sign of the trade. A trade initiated by a market buy order has a sign of 1 and a trade initiated by a market sell order has a sign of -1.

[34] Adverse selection refers to a situation where a market maker trades with an investor who has more information about the value of the stock then the market maker. The adverse selection cost measures how much money market makers would lose in a trade to an investor that possesses more information.

measure that liquidity is worse. The price impact measure is calculated from the share-weighted daily average price impacts of the trades that occur during the day.

- *Log(NBBO Dollar Depth) (MIDAS data):* The logarithm of the cumulative dollar value across all exchanges of the displayed depth in the limit order book at the NBBO.
- *Log(Dollar Depth_1) (MIDAS data):* The logarithm of the cumulative dollar value across all exchanges of the displayed depth in the limit order book at prices within five cents (including the NBBO) of the NBBO.
- *Log(Dollar Depth_3) (MIDAS data):* The logarithm of the cumulative dollar value across all exchanges of the displayed depth in the limit order book at prices within 15 cents (including the NBBO) of the NBBO.
- *Log(Volume $) (CRSP data):* The logarithm of the total dollar volume of shares traded in a stock during the day.
- *Volatility (CRSP data):* Is a relative measure of the stock's daily price volatility. We calculate it from CRSP data as the difference between the highest and lowest transaction price for a stock during the day, divided by the stock's daily closing price.

Quoted spreads, effective spreads, realized spreads, and price impacts are measures of the transactions costs that investors pay to buy and sell stocks. Higher values indicate that it costs more to buy and sell a stock and represent lower market liquidity.

Our measures of depth capture the amount of displayed interest in a stock that is available to be bought or sold across a certain range of prices. A higher value may indicate more of the stock can be bought or sold with a limited impact on the price and could represent greater market liquidity. One limitation of our analysis is that we do not observe hidden depth that is present in the limit order book.[35] This means we are not able to observe the *total* limit order book depth (i.e., displayed plus hidden shares) that is available for execution at each price and cannot draw any conclusions regarding how the total number (dollar value) of shares available

[35] On most US exchanges, traders have the option to not display (i.e., hide) all or a portion of their limit orders from other traders. Although the hidden portion of these orders is available on the limit order book for execution, information about its size (and price if all of the order is hidden) is not disseminated to other traders. The data we use to calculate our depth measures only contains information on the displayed shares available at each price level. Therefore, any analysis we conduct regarding changes in depth as a result of the Pilot are only related to the *displayed* shares. We are not able to observe *total* limit order book depth (i.e., displayed plus hidden shares) and cannot draw any conclusions regarding how the total number (dollar value) of shares available at a given set of prices has changed.

at a given set of prices has changed. Therefore, our depth measures are best thought of as a lower bound on the total depth in the limit order book.

Higher volume may be a proxy for greater liquidity, as more liquid stocks—those with low spreads, high depths, and low price impacts—tend to attract more order flow. Lower volatility may be a proxy for greater liquidity, because it could indicate there is less transitory volatility and more liquidity to absorb the price pressure of large orders.

We also construct the following measures of price efficiency:[36]

- *Rho_FAC:* This is a measure of the absolute value of the first-order autocorrelation of a stock's intraday midpoint returns. A higher value indicates that returns either underreact or overreact more to information and, therefore, prices are less efficient.

- *VR_FAC:* This is a ratio of the variance of a stock's midpoint returns measured at different frequencies. A higher value indicates that the stock's price deviates further from the properties of a random walk and, therefore, prices are less efficient.

- *R2_FAC:* This is a measure of how well lagged market returns predict a stock's midpoint returns.[37] A higher value of this measure indicates more variation in stock returns is explained by lagged market returns, which implies more sluggish incorporation of market-wide information into the stock's price, and, therefore, lower price efficiency.

Rho_FAC, *VR_FAC*, and *R2_FAC* are indices that reflect price *in*efficiency, scored from zero to one. Larger values indicate less efficient prices, i.e., all three measures are inverse measures of price efficiency.

Appendix C provides more details on our market quality measures and also describes control variables we use in our analysis.

Table 1 presents full-sample descriptive statistics of the market quality measures used in our study. Since the stocks in our sample are smaller, they tend to have higher spreads and less depth (see Collver, 2014). From Table 1, we can see that the median relative quoted spread (*Rel Q-spread (TAQ)*) is 18 basis points (bps) and the median relative effective spread (*Rel E-spread (TAQ)*) is 11 bps.[38] Table 1 reports that the median value of the depth in the limit

[36] These are the same price efficiency measures used in Comerton-Forde and Putniņš (2015). See Appendix A of Comerton-Forde and Putniņš (2015) for further details on the price efficiency measures.

[37] This is an intraday version of Hou and Moskowitz's (2005) Price Delay measure.

[38] The median value of *Rel Q-spread (Pilot data)* is 58 bps and the median value of *Rel E-spread (Pilot data)* is 12 bps.

order book within five cents of the NBB and NBO (*Depth_1*) is $45,745. Table 1 also indicates that stocks in our sample are less actively traded; stocks in our sample have an average daily trading volume (*Volume $*) of $5.2 million.

5. Main Tests

This section presents the results of our analysis examining the effects of the Pilot on market quality. We first compare measures of market quality between the pre-Pilot period and the Pilot period for the Control Group and each of the three Test Groups. We then provide an overview of the difference-in-differences analysis, which we use to examine how the Pilot affected market quality in each of the Test Groups, relative to the Control Group, while controlling for unobserved factors that might cause market quality to vary between the pre-Pilot and Pilot periods. In separate subsections, we examine how the Pilot affects market liquidity and price efficiency using this difference-in-differences approach. Finally, we examine how the Pilot differentially affects Pilot stocks with average quoted spreads below and above five cents during the pre-Pilot period.

Overall, we find that increasing the tick size appears to cause market quality to deteriorate. Specifically, on average, we find that, relative to stocks in the Control Group, stocks in the Test Groups experience an increase in transactions costs and volatility and a decrease in price efficiency. The deterioration in market quality appears to be greater for stocks that had average quoted spreads less than the increased tick size (i.e. less than five cents) during the pre-Pilot period. We also find that cumulative displayed depth beyond the best quotes in the limit order book increases when the tick size increases. Our evidence suggests that these findings are mainly driven by the widening of quote increments rather than by imposing a trading increment or a trade-at rule.

5.1 Market quality during the pre-Pilot and Pilot periods.

This subsection presents our analysis comparing our measures of market quality between the pre-Pilot period and the Pilot period.

Table 2 presents the results of a univariate analysis comparing the mean values of our market quality measures during the pre-Pilot period and Pilot period for the Control Group and each of the three Test Groups.[39] Columns 1, 3, 5, and 7 present mean values of the market quality measures during the pre-Pilot period for the Control Group, Test Group 1, Test Group 2, and Test Group 3, respectively. Columns 2, 4, 6, and 8 present mean values for the market quality measures during the Pilot period for these four groups. The table also presents results from

[39] In our sample, the pre-Pilot period occurs between June 2016 and September 2016 and the Pilot period occurs between November 2016 and February 2017.

statistical tests to determine if the difference between market quality measures during the pre-Pilot period and Pilot period are statistically significant.[40]

The results in Table 2 indicate that stocks in all the groups, including the Control Group and the three Test Groups, experience a statistically significant increase in most spread measures between the pre-Pilot period and the Pilot period.[41] These results indicate that transactions costs are greater during the Pilot period for all small-cap stocks, regardless of quoting increment, trading increment, or trade-at treatment.

Table 2 also examines changes in displayed depth between the pre-Pilot period and the Pilot period.[42] The results show evidence that all groups experience an increase in displayed limit order book depth during the Pilot period. Specifically, the results provide evidence that both the displayed depth at the inside quote (*NBBO Dollar Depth*) and cumulative displayed depth within 15 cents of the NBBO (*Depth_*3) increased for all groups. Additionally, the results in Table 2 also indicate that trading volume (*Volume $)* and stock price volatility (*Volatility*) increased for all groups during the Pilot period. Table 2 examines changes in price efficiency and finds evidence that all Tick Size Pilot groups experienced statistically significant increases in price efficiency (*RHO_FAC* and *VR_FAC)* during the Pilot period.

Overall, the results in Table 2 show changes in measures of market quality between the pre-Pilot period and Pilot period in both directions. Transactions costs and volatility increase, but so do depth, trading volume, and price efficiency. These results should be interpreted with caution, however, because they do not control for events unrelated to the Pilot that could also have affected market quality during the two time periods.

5.2 Overview of difference-in-differences methodology

One of the limitations of examining market quality changes between the pre-Pilot and Pilot periods separately for the Control Group and each of the Test Groups is that it does not account for possible differences between the time periods unrelated to the Pilot that could cause variation in market quality.[43] For example, if market wide volatility increased after the Pilot began, the earlier univariate tests might report that some measures of market quality

[40] Specifically, the numbers in parentheses are *t*-statistics from a test of the difference in means between the pre-Pilot period and the Pilot period.

[41] In an unreported test, we find that the significant increases in spreads for the Control Group is largely driven by greater spreads during the month of the presidential election (November 2016).

[42] See supra note 35.

[43] Table 2 provides evidence to support this conclusion, because the market quality measures for the Control Group also changed between the two periods, which suggests that there were influences other than the Pilot that caused market quality to change.

deteriorated during the Pilot period, even if this change was caused by the greater volatility and not the Pilot. This subsection provides an overview of the methodology we use to analyze the effects of the Pilot on market quality controlling for unobserved factors that may have also affected stocks in the Control Group and Test Groups.

We compare the changes in market quality between the Control Group and each Test Group in a difference-in-differences regression. Difference-in-differences is a statistical technique used to mitigate the effects of confounding factors by studying the differential effect of a treatment on a 'Treatment Group' versus a 'Control Group' in an experimental setting. In our setting, we have one Control Group (the Pilot control stocks) and three treatment groups (the three different Pilot Test Groups). The treatments in our sample are the widened minimum quoting and trading increments in the Test Groups. The first set of differences are the changes in the market quality measures *within* the Control Group and each of the three Test Groups after the Pilot begins. The second set of differences, which are commonly referred to as the average treatment effects, are the market quality changes *between* each Test Group and the Control Group.

Although differences-in-differences average treatment effects can be calculated by comparing the average changes in the Test Groups and the Control Group, we calculate the average treatment effects using a regression methodology so that we can better control for differences in firm characteristics and market wide effects that could bias our results. This approach allows us to directly examine the effects of the wider minimum quoting and trading increments on market quality while controlling for certain other confounding factors that might influence market quality during the pre-Pilot or Pilot periods.

Specifically, we perform regression analysis on our stock-day market quality measures that include variables that indicate whether a stock is in any of the Test Groups (*TestGroup*1, *TestGroup*2, *TestGroup*3), a variable that indicates if the time period is during the Pilot period (*Pilot)*, and interaction variables that are constructed by multiplying the Pilot time period variable with each of the Test Group variables (*Pilot* × *TestGroup 1, Pilot* × *TestGroup 2, Pilot* × *TestGroup 3*).[44] We also include variables to control for other factors that might bias our results.[45]

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[44] We estimate the following regression model:

$$MarketQuality_{i,t} = \beta_0 Pilot + \beta_1 TestGroup1 + \beta_2 TestGroup2 + \beta_3 TestGroup3 + \beta_4 Pilot \times TestGroup1 + \beta_5 Pilot \times TestGroup2 + \beta_6 Pilot \times TestGroup3 + \beta_7 Controls + \varepsilon_{i,t},$$

where $Market\ Quality_{i,t}$ is one of the aforementioned market-quality measures for stock *i* on trading date *t*; *Pilot* is an indicator variable that equals 0 if the trading date is during the pre-Pilot period (i.e., before October 3, 2016) and 1 if the trading date is during the Pilot period (i.e., after October 31, 2016). *TestGroup 1* is an indicator variable that equals 1 if a stock is in Test Group 1 and 0 otherwise; *TestGroup 2* is an indicator variable

We present the results from this analysis on our market quality measures in Tables 3, 4, 5, and 6 and discuss the results in the following subsections. When interpreting the regressions results, we are interested in the parameter estimates for the following interaction terms: *Pilot × TestGroup 1, Pilot × TestGroup 2,* and *Pilot × TestGroup* 3. These parameter estimates indicate the average treatment effect of each of the Test Groups and can be interpreted as the difference in the change in the market quality measures between stocks in a specific Test Group and stocks in the Control Group following implementation of the Pilot.

5.3 Market liquidity

Table 3 presents the results of our difference-in-differences analysis for different spread measures, which will help us understand how a wider tick size affects the transactions costs investors pay to execute their orders. Specifically, we examine changes in quoted spreads (denoted by *Rel Q-spread (Pilot)* and *Rel Q-spread (TAQ)),* effective spreads (*Rel E-spread (Pilot)* and *Rel E-spread (TAQ))*, realized spreads (*Rel R-spread*), and price impacts (*Rel Price Impact*).

As discussed earlier, the parameter estimates for the interactions: *Pilot × TestGroup 1, Pilot × TestGroup 2,* and *Pilot × TestGroup* 3, are of interest, because they indicate the average treatment effect of each of the Test Groups. In other words, for each market quality measure, these estimates reflect the difference in the change in the measure between stocks in a specific Test Group and stocks in the Control Group following implementation of the Pilot.

In all of the columns, all of the parameter estimates for the interaction terms are positive and statistically significant, which indicates that, relative to stocks in the Control Group, stocks in all of the Test Groups experience an increase in spreads. Overall, these results suggest that widening the tick size increased transactions costs. Below, we discuss the specific changes in some of our spread measures.

Quoted spreads measure the cost of immediacy and represent the round-trip transactions cost to immediately buy and then sell one share at the NBBO using market orders.[46] When we

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that equals 1 if a stock is in Test Group 2 and 0 otherwise; and *TestGroup 3* is an indicator variable that equals 1 if a stock is a stock in Test Group 3 and 0 otherwise.

[45] Control variables represent firm characteristics and market-level factors. Firm characteristics include average stock price and firm size during the pre-Pilot period, while market-level factors include daily index returns and volatility. We also include month indicator variables in the regressions to control for time effects.

[46] One restriction of our quoted spread measures is that we are only able to observe the best displayed quotes. Since completely hidden orders could lie between the best displayed quotes, it is possible that the true quoted spread (the best bid and offer among both displayed and hidden orders) is different from the displayed quoted spread we observe in our data. Therefore, we are not able to infer any conclusions regarding how the increase in tick sized affected the true quoted spreads.

take a closer look at the results for the relative quoted spread measure in Column 3 of Table 3, *Rel Q-spread (TAQ)*, we find that, relative to stocks in the Control Group, the average quoted spread increased between five and seven bps for stocks in the three Test Groups.[47]

Effective spreads measure the actual transactions costs an investor pays when they buy or sell their shares.[48] When we examine the results in Column 4 of Table 3, *Rel E-spread (TAQ)*, we find that, relative to stocks in the Control Group, the average effective spread increased by six bps for stocks in each of the three Test Groups following the increase in the minimum tick size.

Price impact is the extent to which a trader moves the price when they buy or sell a stock. It is often viewed as a measure of the adverse selection cost for supplying liquidity to traders that might possess private information about the value of the stock. When we examine the results in Column 6 of Table 3, *Rel Price Impact (TAQ)*, we find that, relative to stocks in the Control Group, the average price impact increased by two to four bps for stocks in the three Test Groups.

The realized spread is a measure of the revenue traders earn for supplying liquidity after taking into account the price impact of the transaction. It is equal to the effective spread minus the price impact. When we examine the results in Column 5 of Table 3, *Rel R-spread (TAQ)*, we find that, relative to stocks in the Control Group, the average realized spread increased by two to four bps for stocks in the three Test Groups following the increase in the minimum tick size.

We also perform statistical tests to examine whether the different quoting and trading restrictions in each of the Test Groups caused different changes in our spread measures. The results are presented in rows, *G1 vs. G2*, *G1 vs. G3*, and *G2 vs. G3* of Table 3. *G1 vs. G2* tests if there is a difference in the changes in Test Group 1 and Test Group 2; *G1 vs. G3* tests if there is a difference in the changes in Test Group 1 and Test Group 3; and *G2 vs. G3* tests if there is a difference in the changes in Test Group 2 and Test Group 3.[49] The results indicate that there is a statistically significant difference in the change between the Test Groups for the

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[47] In an unreported test, we also examine the closing bid-ask spread measure (Chung and Zhang, 2014), which measures the difference between the closing bid and ask quotes, relative to the closing price. The results are similar to the results reported for the intraday quoted spread measures in Table 3, i.e. we find that, relative to stocks in the Control Group, stocks in the Test Groups experience a significant increase in closing bid-ask spread.

[48] The effective spread could differ from the quoted spread if an investor's order is executed, either via their broker or against hidden liquidity on an exchange, at a better price than the best displayed quote.

[49] *G1 vs. G2*, *G1 vs. G3*, and *G2 vs. G3* present the differences among the coefficients on the interaction terms and *t*-statistics on whether these differences are significantly different from zero.

realized spreads, *Rel R-spread (TAQ)*, and price impact, *Rel Price Impact (TAQ)*.[50] The price impact appears to increase more and the realized spread increases less for stocks in Test Group 3 compared to stocks in Test Groups 1 and 2. Because there is little difference in changes in the other spread measures across the Test Groups, we conclude that the changes in transactions costs appear to be mainly driven by changes in quoting increments and not by changes in trading increments or the "trade at" restriction.

Table 4 presents the results of our difference-in-differences analysis examining how the Pilot affects our different measures of displayed depth. This will help us understand how a wider tick size affects the amount of displayed interest in a stock that is available to be bought or sold across a certain range of prices. Specifically, we examine changes in several measures of displayed depth including: the logarithm of the cumulative dollar value of displayed shares across all exchanges at the best quotes (*Log(NBBO Dollar Depth)*), the logarithm of the cumulative dollar value of displayed shares across all exchanges within 5 cents of the best quotes (*Log(Depth_1)*), and the logarithm of the cumulative dollar value of displayed shares across all exchanges within 15 cents of the best quotes (*Log(Depth_3)*).

As with our analysis of transactions cost measures, we are particularly interested in the average treatment effect of each of the Test Groups on market depth. A positive estimate of the average treatment effect would indicate that displayed depth increased in the Test Group, relative to the Control Group, during the Pilot period. This could be an indication that market liquidity improves, but the results need to be interpreted with caution. As discussed above, we are not able to observe hidden depth that is present in the limit order book, which means we are not able to observe the *total* limit order book depth (i.e. displayed depth plus hidden depth) that is available for execution at each price. An increase in displayed depth could indicate that the total depth increased but the percentage of depth that was hidden stayed the same, the total depth remained the same but the percentage of depth that was hidden decreased, or some combination of both. Therefore, we cannot draw any conclusions regarding how the total number (dollar value) of shares available at a given set of prices has changed—only the change in displayed depth.[51]

Column 1 examines the effects of the tick size change on the cumulative dollar value of displayed shares at the NBBO across all exchanges (*Log(NBBO Dollar Depth)*). The coefficients on all interaction terms are positive and statistically significant. This indicates that, relative to stocks in the Control Group, stocks in the Test Groups experience an increase

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[50] Specifically, we find that the coefficient on *Pilot* × *TestGroup 3* is significantly smaller than *Pilot* × *TestGroup 1* and *Pilot* × *TestGroup 2* for *Rel R-spread (TAQ)* and significantly larger for *Rel Price Impact (TAQ)*.

[51] See supra note 35.

in the displayed depth at the best quotes. However, these results should be viewed with caution, because depth at the best quotes is likely to mechanically increase when the minimum tick size widens. When the tick size widens, depth that previously would have been at multiple price levels is consolidated at one price level.

In order to control for this mechanical increase in depth, in Column 2 we also conduct tests to examine whether increasing the tick size affects cumulative displayed depth within 5 cents of the best quotes (*Log(Depth_1)*). The coefficients on the interaction terms for Test Groups 1 and 2 are not statistically significant. This indicates that, we cannot conclude with a high degree of statistical confidence that changes in displayed depth for stocks in Test Group 1 and Test Group 2 during the Pilot period, relative to the Control Group, were not a result of chance. These findings are largely consistent with prior studies on decimalization that found that depth at the best quotes *mechanically* declined with decimalization (e.g., Bessembinder, 2003; Chakravarty, Harris, and Wood, 2001), but the cumulative depth did *not* significantly change (Bacidore, Battalio, and Jennings, 2003). However, relative to stocks in the Control Group, stocks in Test Group 3 did experience a statistically significant increase in their cumulative displayed depth within 5 cents of the best quotes, which could indicate that the "trade-at" restriction increases displayed depth.[52]

In Column 3, we examine the cumulative displayed limit order book depth within 15 cents of the NBBO. The coefficients on the interaction terms are all positive and statistically significant, which indicates that, relative to stocks in the Control Group, cumulative displayed limit order book depth within 15 cents of the NBBO increased for stocks in all three Test Groups when the tick size increased. This increase indicates that cumulative displayed depth at prices in the limit order book above the best quotes increased with the wider tick size.[53]

We also perform statistical tests to examine whether the different quoting and trading restrictions in each of the Test Groups caused different changes in our depth measures. The results are presented in rows, *G1 vs. G2*, *G1 vs. G3*, and *G2 vs. G3* of Table 4. We find that the displayed depth at the NBBO increased more for stocks in Test Group 3 than for stocks in Test Groups 1 and 2.[54] This could indicate that the "trade at" restriction increased the

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[52] Specifically, it is the minimum quoting and trading increase combined with the "trade-at" rule that might cause the displayed depth to increase. The tests comparing the changes in Test Group 3 to Test Groups 1 and 2, *G1 vs. G3* and *G2 vs. G3*, indicate that differences between these groups are not statistically significant, which suggests that the marginal impact of the "trade-at" rule, over and above the change caused by the increased tick size, on displayed depth was not significant.

[53] In unreported tests, we also find that the logarithm of the cumulative displayed dollar depth between prices 6 to 10 cents away from the NBBO and 11 to 15 cents away from the NBBO also increased for all three Test Groups.

[54] Specifically, we find that the coefficient on *Pilot × TestGroup 3* is significantly larger than *Pilot × TestGroup 1* and *Pilot × TestGroup 2* for *Log(NBBO Dollar Depth).*

incentives for traders to display an order at the NBBO, because of the "trade at" restriction. . When we examine cumulative displayed depth within five and fifteen cents of the NBBO, we do not find statistically significant differences across Test Groups for nearly all our tests, which suggests that the increase in cumulative depths beyond the best quotes is mainly driven by changes to quoting increments and not changes to trading increments or imposing a "trade at" restriction.

Table 5 presents the results of our difference-in-differences analysis examining how the Pilot affects trading volume (*Log*(*Volume $*)) and stock return volatilities (*Volatility*). An increase in trading volume or a decrease in volatility could indicate that market liquidity improves.

Column 1 reports results for trading volume (*Log*(*Volume $*)). The coefficients are all negative and statistically insignificant. This suggests that, relative to stocks in the Control Group, stocks in the Test Groups did not experience a significant change in trading volume when the tick size increased.

Column 2 reports results for the effects of the Pilot on stock return volatilities. The coefficients on the interaction terms are all positive and statistically significant, suggesting that stocks in the Test Groups experienced an increase in stock return volatility when the tick size increases. A positive relation between tick size and stock return volatility is consistent with the findings in prior studies, e.g., Ronen and Weaver (2001) and Bessembinder (2003) and could indicate that market liquidity deteriorates when the tick size increases.

In summary, we find that stocks in the Test Groups experienced a significant increase in spreads and volatility when the tick size increases. These results indicate that transactions costs increased and the liquidity dimension of market quality deteriorated when the minimum tick size widens during the Pilot. However, we also find an increase in cumulative displayed depth beyond the best quotes.[55]

5.4 Price efficiency

Table 6 presents the results of our difference-in-differences analysis examining how the Pilot affects our price efficiency measures, which will help us understand how a wider tick size affects how well prices reflect all available information. Specifically, we examine changes in several price efficiency measures including: the autocorrelation of midpoint returns (*Rho_FAC*), the ratio of the variances of midpoint returns measured at different frequencies

[55]. See supra note 35.

(*VR_FAC*), and the speed at which market-wide information is compounded into individual stock returns (*R2_FAC*).[56]

These measures capture different dimensions of price inefficiency. A higher value of *Rho_FAC* indicates that prices adjust to new information slowly over time and not immediately. A higher value of *VR_FAC* indicates that markets are less efficient, if for example variances sampled at five-minute intervals are significantly larger than variances sampled at one-minute intervals.[57] A higher value of *R2_FAC* indicates that markets are less efficient, as it takes longer for market wide information to be incorporated into individual stock prices.

The results in Table 6 indicate that the parameter estimates on the interaction terms are all positive and statistically significant for the regressions of *VR_FAC* and *R2_FAC*. These results suggest that, relative to stocks in the Control Group, stocks in the Test Groups experience a decrease in price efficiency during the Pilot period. These results indicate that widening the minimum tick size decreases the speed at which a stock's price incorporates new information and causes the stock's price to further deviate from the properties of a random walk. These results indicate the price efficiency dimension of market quality deteriorates when the tick size widens and are broadly consistent with the findings of Chordia, Roll, and Subrahmanyam (2008), which finds that a smaller tick size improves price efficiency.

We also perform statistical tests to examine whether the different quoting and trading restrictions in each of the Test Groups caused different changes in our price efficiency measures. The results are presented in rows, *G1 vs. G2*, *G1 vs. G3*, and *G2 vs. G3* of Table 6. None of these results are statistically significant, which suggests that the negative effect of the Tick Size Pilot on price efficiency is mainly driven by the change in the quoting increments and not the change in the trading increments or the "trade at" restriction.

In summary, the findings in Table 6 suggest that an increase in tick size results in deterioration in the price efficiency dimension of market quality.

5.5 Analysis of changes in market quality for stocks with spreads above and below five cents

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[56] *R2_FAC* is formally defined as the correlation between lagged market returns and a stock's midpoint returns. A midpoint return is the percentage change in the midpoint of a stock's bid and ask quotes.

[57] Specifically, *VR_FAC* is based on the "random walk hypothesis" of stock prices which implies that five-minute stock return variances should be exactly five times that of one-minute stock return variances. Any difference (higher or lower) indicates a deviation from a statistical random walk, and is usually interpreted as evidence of market frictions.

We found that some stocks included in the Pilot sample had average quoted spreads less than five cents during the pre-Pilot period. For these stocks, the tick size change could have a more pronounced effect on market quality. Some prior studies examining tick size reductions have found the effects of a tick size reduction are greater in low-priced stocks, which are more likely to have smaller dollar quoted spreads.[58]

Table 7 presents the results of our analysis separately examining the effects of the Pilot on market quality for stocks with average quoted spreads below and above five cents during the pre-Pilot period. We sort stocks into two groups based on whether their average quoted spread, *Rel Q-spread (TAQ)*, during the pre-Pilot period is less than five cents (<*$0.05*) or greater than or equal to five cents (>=*$0.05*). We then perform our difference-in-differences analysis for changes in market quality separately for stocks in the two groups. Panel A reports results examining changes in relative quoted and effective spreads, Panel B reports results for changes in price efficiency, Panel C reports results for changes in limit order book depth, and Panel D reports results for changes in trading volume and volatility. Even numbered columns contain the results of the analysis for stocks with pre-Pilot average quoted spreads less than five cents (<*$0.05*) and odd numbered columns contain the results for stocks with average quoted spreads greater than five cents (>=*$0.05*).

Panel A examines changes in relative quoted and effective spreads. A positive coefficient would indicate that relative quoted and effective spreads increased for stocks in the Test Group, relative to the Control Group, during the Pilot period and would indicate the transaction cost dimension of market liquidity increased.

The results show that the effects of the tick size increase are different across the two subsamples. For example, the parameter estimates for the interaction terms in columns 1, 3, 5, and 7 are all positive and statistically significant. This indicates stocks in the Test Groups that had pre-Pilot average quoted spreads less than five cents (<*$0.05*) experience increases in quoted and effective spreads, relative to stocks in the Control Group, when the tick size increases.

In contrast, the results in columns 2 and 6 show no statistical significance, which indicates stocks in the Test Groups that had pre-Pilot average quoted spreads greater than or equal to five cents (>=*$0.05*) likely did not experience increases in quoted spreads when the tick size increased.

The analysis for the change in effective spreads for stocks in the Test Groups that had pre-Pilot average quoted spreads above five cents (>=*$0.05*) produced mixed results. The parameter estimates for the interaction terms in column 4, which are effective spreads

[58] See Bollen and Busse (2006) and Chung and Chuwonganant (2004).

calculated using the Pilot order based data, are all positive and statistically significant. In column 8, which are effective spreads calculated using the TAQ trade based data, none of the parameter estimates are statistically significant. These results could indicate that larger orders in stocks in the Test Groups with pre-Pilot average quoted spreads above five cents (>=*$0.05*) experienced an increase in effective spreads when the tick size widened, but smaller orders did not.

Panel B examines changes in price efficiency. Since our measures are inverse measures of price efficiency, a positive coefficient indicates that the price efficiency dimension of market quality decreased for stocks in the Test Group, relative to the Control Group, during the Pilot period.

The coefficients on the interactive terms in the odd numbered columns (Columns 9, 11, and 13) are all positive and statistically significant, which indicates that, relative to the Control Group, price efficiency deteriorated for stocks with pre-Pilot average quoted spreads less than five cents (<*$0.05*) in the Test Groups after the tick size widened.

The price efficiency results are mixed for stocks in the Test Groups with pre-Pilot average quoted spreads greater than or equal to five cents (>=*$0.05*). In Column 10, which shows the results for the change in the price efficiency measure for the autocorrelation of midpoint returns (*Rho_FAC*), the coefficients on the interaction terms for Test Groups 1 and 3 are negative and statistically significant, which indicates price efficiency improved.[59] More specifically, the results indicate that prices adjust to new information quicker for stocks with pre-Pilot average quoted spreads above five cents (>=*$0.05*) in Test Groups 1 and 3 when the tick size widened.

In contrast, the coefficients on the interaction terms for the other two price efficiency measures in Columns 12 and 14 (*V2_FAC* and *R2_FAC*) are all positive and statistically significant, which indicates price efficiency deteriorated.[60] However, the magnitude of the coefficients (Columns 12 and 14) for stocks with pre-Pilot average quoted spreads greater than or equal to five cents (>=*$0.05*) is less than the magnitude of the coefficients (Columns 11 and 13) for stocks with pre-Pilot average quoted spreads less than five cents (<*$0.05*), which indicates the tick size increase caused price efficiency to deteriorate more for stocks with pre-Pilot average quoted spreads less than the widened tick size (<*$0.05*), i.e., five cents.

Panel C examines changes in displayed limit order book depth. All the interaction coefficients are positive and statistically significant for displayed depth at the NBBO

[59] The coefficient on the interaction term for Test Group 2 is statistically insignificant.
[60] More specifically the results indicate that widening the minimum tick size for Test Group stocks with pre-Pilot average quoted spreads above five cents (>=*$0.05*) increases the stock price's deviation from the properties of a random walk and also increases the time it takes for the stock's price to incorporate market wide information.

(Columns 15 and 16) and displayed depth within fifteen cents of the NBBO (Columns 19 and 20).[61] This indicates that displayed depth at the best quotes and displayed depth at prices in the limit order book above the best quotes increased for both Test Group stocks with pre-Pilot average quoted spreads above (>=*$0.05*) and below (<*$0.05*) five cents when the tick size widened. However, the magnitude of the coefficients (Columns 15 and 19) is greater for Test group stocks with pre-Pilot average quoted spreads less than five cents (<*$0.05*), which indicates these stocks had a greater increase in displayed limit order book depth.

Panel D examines changes in trading volume and volatility. In the results for the trading volume regressions, all of the interactive coefficients are statistically insignificant (Columns 21 and 22). This indicates that widening the tick size did not cause a significant change in trading volume for either Test Group stocks with pre-Pilot average quoted spreads above (>=*$0.05*) or below (<*$0.05*) five cents. For volatility, all of the interaction coefficients for Test group stocks with pre-Pilot average quoted spreads less than five cents (Column 23) are positive and statistically significant. In contrast, the interactions coefficients for most Test group stocks with pre-Pilot average quoted spreads greater than or equal to five cents (Column 24) are insignificant.[62] This indicates that widening the tick size increased volatility for stocks with pre-Pilot average quoted spreads less than the widened tick size, i.e., five cents.

Overall, these results indicate stocks with pre-Pilot average quoted spreads less than the widened tick size (<*$0.05*), i.e., five cents, experienced a greater increase in transactions costs and volatility and a greater deterioration in price efficiency when the tick size increased than stocks with pre-Pilot average quoted spreads greater than the widened tick size (>=*$0.05*). However, stocks with pre-Pilot average quoted spreads less than five cents (<*$0.05*) also experienced a greater increase in displayed limit order book depth at the best quotes and displayed depth at prices in the limit order book above the best quotes when the tick size increased than stocks with pre-Pilot average quoted spreads greater than five cents (>=*$0.05*).

6. Supplemental Tests

This section presents supplemental tests examining how the Pilot affects the transactions costs of orders of different sizes.

Our results in Table 3 indicate that the wider tick size during the Pilot caused spreads to increase. This results in higher transactions costs for small-sized orders. However, the

[61] The coefficient on the interaction term for Test Group 3 in Column 17 is also positive and statistically significant. This indicates that the wider tick size increased displayed depth within five cents of the NBBO for stocks in Test Group 3 with pre-Pilot average quoted spreads less than five cents (<*$0.05*).
[62] The interaction coefficient for Test Group 1 is negative and statistically significant at the 10% significance level.

increase in displayed limit order book depth we observe in Table 4 makes it uncertain what will happen to the transactions costs of larger orders. Theoretically, an increase in depth could reduce the transactions costs for larger orders, because submitters of large orders could execute a larger portion of their orders at quotes near the NBBO before moving to prices deeper in the limit order book to execute the remainder of their orders. Prior studies examined changes in the transactions costs of large orders when the tick size was reduced during decimalization and found mixed results. Some studies find that transactions costs for larger orders decline after decimalization (see Bacidore, Battalio, and Jennings, 2003; Chakravarty, Panchapagesan, and Wood, 2005; and Werner, 2003). While other studies (see Chakravarty, Harris, and Wood, 2001) find that the transactions costs for large trades do not change following decimalization.

A limitation of the TAQ data is that it only contains information on trades and not orders. This means that larger market orders that execute against multiple limit orders would appear as separate transactions in the TAQ data, so the effective spread for the entire order could not be calculated. One advantage of the Pilot data is that it contains information on orders, so we are able to observe the effective spread of different-sized orders.

Table 8 presents the results of our difference-in-differences analysis examining how the Pilot affects the relative effective spread measure for orders of different sizes. These results help us understand how a wider tick size affects the transactions costs for orders of different sizes. According to the Pilot data description, *Order size 0* includes orders of less than 100 shares; *Order size 1* includes orders of 100 to 499 shares; *Order size 2* includes orders of 500 to 1,999 shares; *Order size 3* includes orders of 2,000 to 4,999 shares; *Order size 4* includes orders of 5,000 to 9,999 shares; and *Order size 5* includes orders of 10,000 shares or larger.[63] Specifically, we examine changes in the relative effective spread measure for each of the order size categories. Positive coefficient estimates for a size category suggest that transactions costs increased in that order size category and that the liquidity dimension of market quality deteriorated with the wider tick size.

The results in Table 8 report the parameter estimates on the interaction terms are all positive and statistically significant for all of the Test Groups and across all of the order size categories. This indicates that transactions costs increased for all order sizes when the tick size widened. More importantly, Table 8 indicates that the coefficients on the interaction

[63] Note that the Pilot Order Size categories are based on the number of shares submitted in the order and not the number of shares that execute in trades. It is possible that not all of the shares in the order execute.

terms have similar magnitudes across the different order size categories, which indicates the change in transactions costs is similar for all order sizes.[64]

In unreported results, we also examine whether the different quoting and trading restrictions in each of the Test Groups caused different changes in the relative effective spreads of different order sizes. The results did not indicate there was a statistically significant difference in the changes across the different Test Groups in any of the order size categories. This suggests the change in transactions costs is mainly driven by the change in the quoting increments and not the change in the trading increments or the "trade at" restriction.

7. Conclusion

In this study we use the Tick Size Pilot Plan as a controlled experiment to examine how an increase in tick size affects the market quality of Pilot stocks. Using a difference-in-differences analysis, we compare differences in the changes in the market quality measures between stocks in the Test Groups and stocks in the Control Group. Our findings suggest that, relative to stocks in the Control Group, stocks in the Test Groups experience a reduction in market quality when the tick size widens.

Specifically, we find that quoted spreads, effective spreads, realized spreads, price impacts, and stock return volatilities increased, and that price efficiency declined for stocks in the Test Groups after the tick size widened. We find that displayed depth at the best quotes increased in all the Test Groups, but the total displayed depth within five cents of the best quotes only increased for Test Group stocks subject to the "trade-at" restriction. We also find that all Test Groups experience an increase in cumulative displayed depth beyond the best quotes. However, this increase in displayed depth does not appear to improve the transactions costs of large orders, which also increased when the tick size widened. Furthermore, we find that the deterioration in market quality appears to be greater for stocks that had average quoted spreads less than the Pilot period tick size (i.e., less than five cents) during the pre-Pilot period. Because we find little variation in the changes in market quality across the different Test Groups, our evidence suggests that our results are mainly driven by the increase in the size of quoting increments, and not an increase of in the size of trade increments or implementation of the "trade-at" rule.

Some participants at the SEC Decimalization Roundtable argued that a larger tick size can provide market makers with greater incentives to make markets and therefore could improve stock market quality. We do not find convincing evidence that a wider tick size improves

[64] In unreported results we also separately examine the change in transaction costs for different sized orders for stocks with pre-Pilot average quoted spreads less than five cents and stocks with pre-Pilot average quoted spreads greater than or equal to five cents. We find that transaction costs increased for all order sizes for both stocks with pre-Pilot average quoted spreads less than and greater than five cents.

market quality, on average. Instead, our findings suggest that increasing the tick size from one cent to five cents reduces market quality on average.

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Table 1. Summary Statistics

This table presents descriptive statistics for the market quality measures. The statistics are calculated from the full sample of Pilot Stocks measured over the Pre-Pilot and Pilot periods. Please refer to Appendix B for detailed definitions of the variables.

Variable	Mean	SD	Q1	Median	Q3
Rel Q-spread (Pilot)	0.01123	0.01510	0.00297	0.00586	0.01326
Rel E-spread (Pilot)	0.00306	0.00554	0.00059	0.00124	0.00304
Rel Q-spread (TAQ)	40.74761	99.09107	9.33247	17.72854	42.69765
Rel E-spread (TAQ)	25.58289	44.08311	5.59051	11.07040	27.06823
Rel R-spread (TAQ)	16.75149	40.85259	1.36520	4.55138	16.20405
Rel Price Impact (TAQ)	8.83667	22.15905	2.84159	4.80476	8.65929
NBBO Dollar Depth (MIDAS)	60,893	1,403,496	9,693	18,545	35,340
Dollar Depth_1 (MIDAS)	98,406	1,274,901	22,679	45,745	83,221
Dollar Depth_3 (MIDAS)	237,701	1,812,126	57,966	121,083	236,682
RHO_FAC	0.12717	0.11575	0.05353	0.09066	0.15749
VR_FAC	0.45249	0.17383	0.29627	0.44994	0.58237
R2_FAC	0.68002	0.28853	0.43857	0.76305	0.94861
Volume $ (CRSP)	5,240,828	10,149,678	292,820.00	1,657,750	5,941,937
Volatility (CRSP)	0.03523	0.02789	0.01812	0.02777	0.04363

Table 2. Univariate Tests

This table presents the mean value of the market quality measures for stock-day observations in the Control Group and each of the Test Groups during the pre-Pilot period (June 2016-September 2016) and Pilot period (November 2016-February 2017). The Control Group of the Tick Size Pilot program consists of around 1,200 stocks, while each of the 3 Test Groups consists of around 400 stocks. Please refer to Section 3 for an introduction to the Tick Size Pilot program. Please refer to Appendix B for detailed definitions of the variables. Parentheses contain t-statistics testing whether the mean of a market quality measure is equal during the pre-Pilot and Pilot periods. *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Control Group pre-Pilot	Control Group Pilot	Test Group 1 pre-Pilot	Test Group 1 Pilot	Test Group 2 pre-Pilot	Test Group 2 Pilot	Test Group 3 pre-Pilot	Test Group 3 Pilot
Rel Q-spread (Pilot)	0.01064	0.01119	0.01048	0.01242	0.01117	0.01293	0.01035	0.01246
t-stat (pre vs. post)		(3.65)***		(5.15)***		(4.93)***		(7.46)***
Rel E-spread (Pilot)	0.00214	0.00285	0.00215	0.00519	0.00228	0.00544	0.00214	0.00539
t-stat (pre vs. post)		(12.25)***		(15.95)***		(15.49)***		(17.91)***
Rel Q-spread (TAQ)	36.71309	41.96609	36.08817	48.01816	38.48564	49.27297	35.09354	47.45487
t-stat (pre vs. post)		(7.17)***		(8.78)***		(7.99)***		(9.52)***

Rel E-spread (TAQ)	23.7227	24.70861	23.28743	30.80371	25.30219	32.21013	22.70112	29.88792
t-stat (pre vs. post)		(2.31)**		(7.83)***		(7.74)***		(9.52)***
Rel R-spread (TAQ)	15.69	16.13773	15.80122	20.45433	17.0283	21.47824	15.04006	17.72042
t-stat (pre vs. post)				(5.74)***		(5.57)***		(4.32)***
Rel Price Impact (TAQ)	8.04 (1.26)	8.58	7.50	10.35	8.28	10.76	7.67	12.16
t-stat (pre vs. post)		(2.78)***		(10.72)***		(7.86)***		(17.31)***
NBBO Dollar Depth (MIDAS)	20,208.50	33,484.26	23,742.20	197,866.87	24,959.62	162,427.09	20,781.67	192,060.50
t-stat (pre vs. post)		(2.87)***		(2.45)**		(2.60)***		(4.50)***
Dollar Depth_1 (MIDAS)	71,678.00	96,109.00	83,576.00	177,698.00	72,602.00	135,780.00	78,622.00	173,856.00
t-stat (pre vs. post)		(2.69)***		(1.55)		(1.53)		(3.01)***
Dollar Depth_3 (MIDAS)	185,710.00	208,278.00	206,295.00	398,267.00	181,328.00	337,853.00	202,465.00	442,391.00
t-stat (pre vs. post)		(2.12)**		(1.78)*		(1.93)*		(3.75)***

RHO_FAC (TAQ)	0.13301	0.1207	0.13226	0.12201	0.13262	0.1216	0.13283	0.12015
t-stat (pre vs. post)		(-13.03)***		(-5.95)***		(-6.70)***		(-7.84)***
VR_FAC (TAQ)	0.55086	0.35479	0.5491	0.38096	0.54852	0.3805	0.54798	0.37951
t-stat (pre vs. post)		(-147.93)***		(-58.85)***		(-55.33)***		(-56.34)***
R2_FAC (TAQ)	0.64571	0.68806	0.64108	0.76008	0.63742	0.76365	0.64964	0.77213
t-stat (pre vs. post)		(18.76)***		(16.80)***		(15.76)***		(16.44)***
Volume $ (CRSP)	4,773,248.04	5,781,602.83	4,913,045.40	5,832,775.78	4,893,482.45	5,794,399.11	5,011,477.27	5,728,427.30
t-stat (pre vs. post)		(9.65)***		(4.78)***		(5.16)***		(3.15)***
Volatility (CRSP)	0.03356	0.03643	0.03298	0.03697	0.03389	0.03785	0.0332	0.03738
t-stat (pre vs. post)		(10.22)***		(7.91)***		(7.99)***		(8.94)***

Table 3. Difference-in-Differences Regressions of Bid-Ask Spreads

This table presents a difference-in-differences analysis to investigate how the tick size change alters the bid-ask spreads of stocks in the Test Groups compared to stocks in the Control Group. The regression specification is given by:

$$Spread_{i,t} = \beta_0 Pilot + \beta_1 TestGroup1 + \beta_2 TestGroup2 + \beta_3 TestGroup3 + \beta_4 Pilot \times TestGroup1 + \beta_5 Pilot \times TestGroup2 + \beta_6 Pilot \times TestGroup3 + \beta_7 Controls + \varepsilon_{i,t},$$

where $Spread_{i,t}$ represents several bid-ask spread measures such as *Rel Q-spread (Pilot), Rel E-spread (Pilot), Rel Q-spread (TAQ), Rel E-spread (TAQ), Rel R-spread (TAQ)*, and *Rel Price Impact (TAQ)*. *Pilot* is a dummy variable that equals 0 if the trading date is during the pre-Pilot period (i.e., before October 3, 2016) and 1 if the trading date is during the Pilot period (i.e., after October 31, 2016). *TestGroup 1* is a dummy variable that equals 1 if a stock is in Test Group 1 and 0 otherwise; *TestGroup 2* is a dummy variable that equals 1 if a stock is in Test Group 2 and 0 otherwise; and *TestGroup 3* is a dummy variable that equals 1 if a stock is in Test Group 3 and 0 otherwise. The interaction terms, *Pilot* × *TestGroup 1, Pilot* × *TestGroup 2,* and *Pilot* × *TestGroup 3*, are constructed by multiplying the *Pilot* dummy with the three Test-Group dummy variables. The last 3 rows of the table (*G1 vs. G2*, *G1 vs. G3*, and *G2 vs. G3*) present the differences among the coefficients on *Pilot* × *TestGroup 1, Pilot* × *TestGroup 2,* and *Pilot* × *TestGroup 3* and *t*-statistics that measure the normalized distance between these differences and zero. Control variables include: the average firm closing stock price (*Price)* and market capitalization (*MktCap*) during the pre-Pilot period, value weighted daily market returns (*MktReturn*), the daily price volatility of the SPY (*SPYvolatility*), the daily opening value of the VIX volatility index (*VIX*), and month indicator variables to control for time effects. Please refer to Appendix B for detailed variable definitions. Numbers in parentheses are the t-statistics. *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent Variables	Rel Q-spread (Pilot)	Rel E-spread (Pilot)	Rel Q-spread (TAQ)	Rel E-spread (TAQ)	Rel R-spread (TAQ)	Rel Price Impact (TAQ)
Pilot × TestGroup 1	0.00132*** (3.27)	0.00230*** (11.65)	6.28861*** (4.09)	6.21585*** (5.99)	4.06698*** (4.62)	2.13361*** (6.71)
Pilot × TestGroup 2	0.00127*** (3.34)	0.00248*** (11.75)	5.76429*** (3.80)	6.10477*** (6.26)	4.1335*** (4.77)	1.99195*** (5.40)
Pilot × TestGroup 3	0.00154*** (4.84)	0.00255*** (13.36)	7.27129*** (4.89)	6.32285*** (7.34)	2.31212*** (3.25)	3.98388*** (12.34)
Pilot	0.00023 (1.29)	0.00050*** (7.93)	-3.95525*** (-4.74)	0.86925 (1.64)	0.32837 (0.69)	0.54295*** (2.63)
TestGroup dummies	Yes	Yes	Yes	Yes	Yes	Yes
Month dummies	Yes	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes	Yes
R2	0.2	0.21	0.07	0.14	0.09	0.05
N	384,627	383,923	379,787	379,664	379,653	379,262
Test on interaction term						
G1 vs. G2	-0.00005 (-0.09)	0.00018 (0.65)	-0.52432 (-0.28)	-0.11108 (-0.09)	0.06652 (0.06)	-0.14166 (-0.35)
G1 vs. G3	0.00022 (0.46)	0.00025 (0.95)	0.98268 (0.52)	0.10701 (0.09)	-1.75486* (-1.72)	1.85028*** (5.14)
G2 vs. G3	0.00026 (0.58)	0.00007 (0.26)	1.507 (0.81)	0.21809 (0.19)	-1.82138* (-1.81)	1.99193*** (4.91)

Table 4. Difference-in-Differences Regressions of Market Depth

This table presents the difference-in-differences analysis to investigate how the tick size change alters the limit order book depth of stocks in the Test Groups compared to stocks in the Control Group. The regression specification is given by:

$$Depth_{i,t} = \beta_0 Pilot + \beta_1 TestGroup1 + \beta_2 TestGroup2 + \beta_3 TestGroup3 + \beta_4 Pilot \times TestGroup1 + \beta_5 Pilot \times TestGroup2 + \beta_6 Pilot \times TestGroup3 + \beta_7 Controls + \varepsilon_{i,t},$$

where $Depth_{i,t}$ represents several quote size and market depth measures such as *Quote Depth, Log (Depth_1),* and *Log(Depth_3). Quote Depth* is the share-weighted average of Same Side Quoted Depth (from the Pilot data) for a stock-day observation. *Log(Depth_1)* is the logarithm of cumulative dollar depth within **five** cents of the NBBO, while *Log(Depth_3)* is the logarithm of cumulative dollar depth within **15** cents of the NBBO. *Pilot* is a dummy variable that equals 0 if the trading date is during the pre-Pilot period (i.e., before October 3, 2016) and 1 if the trading date is during the Pilot period (i.e., after October 31, 2016). *TestGroup 1* is a dummy variable that equals 1 if a stock is in Test Group 1 and 0 otherwise; *TestGroup 2* is a dummy variable that equals 1 if a stock is in Test Group 2 and 0 otherwise; and *TestGroup 3* is a dummy variable that equals 1 if a stock is in Test Group 3 and 0 otherwise. The interaction terms, *Pilot* × *TestGroup 1, Pilot* × *TestGroup 2,* and *Pilot* × *TestGroup 3*, are constructed by multiplying the *Pilot* dummy with the three Test-Group dummy variables. The last 3 rows of the table (*G1 vs. G2*, *G1 vs. G3*, and *G2 vs. G3*) present the differences among the coefficients on *Pilot* × *TestGroup 1, Pilot* × *TestGroup 2,* and *Pilot* × *TestGroup 3* and *t*-statistics that measure the normalized distance between these differences and zero. Control variables include: the average firm closing stock price (*Price)* and market capitalization (*MktCap*) during the pre-Pilot period, value weighted daily market returns (*MktReturn*), the daily price volatility of the SPY (*SPYvolatility*), the daily opening value of the VIX volatility index (*VIX*), and month indicator variables to control for time effects. Please refer to Appendix B for detailed variable definitions. Numbers in parentheses are the t-statistics. *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

	(1)	(2)	(3)
Dependent Variables	Log(NBBO Dollar Depth) (MIDAS)	Log(Dollar Depth_1) (MIDAS)	Log(Dollar Depth_3) (MIDAS)
Pilot × TestGroup 1	1.09616*** (32.37)	0.01562 (0.53)	0.16109*** (5.62)
Pilot × TestGroup 2	1.09017*** (32.03)	0.03775 (1.30)	0.19261*** (6.73)
Pilot × TestGroup 3	1.20009*** (33.94)	0.07347*** (2.58)	0.24918*** (8.76)
Pilot	0.22408*** (17.51)	0.10789*** (7.55)	0.02264 (1.63)
TestGroup dummies	Yes	Yes	Yes
Month dummies	Yes	Yes	Yes
Controls	Yes	Yes	Yes
R2	0.54	0.33	0.34
N	384,629	379,715	379,715
Test on interaction term			
G1 vs. G2	-0.00599 (-0.13)	0.02213 (0.58)	0.03152 (0.84)
G1 vs. G3	0.10393*** (2.22)	0.05785 (1.54)	0.08808** (2.37)
G2 vs. G3	0.10992*** (2.34)	0.03572 (0.96)	0.05657 (1.52)

Table 5. Difference-in-Differences Regressions of Volume and Volatility

This table presents the difference-in-differences analysis to investigate how the tick size change alters trading volume and volatility for stocks in the Test Groups compared to stocks in the Control Group. The regression specification is given by:

$$Volume\ or\ Volatility_{i,t} = \beta_0 Pilot + \beta_1 TestGroup1 + \beta_2 TestGroup2 + \beta_3 TestGroup3 + \beta_4 Pilot \times TestGroup1 + \beta_5 Pilot \times TestGroup2 + \beta_6 Pilot \times TestGroup3 + \beta_7 Controls + \varepsilon_{i,t},$$

where $Volume_{i,t}$ is the dollar trading volume of a stock on a given date and $Volatility_{i,t}$ is the stock price volatility of a stock on a given date, defined as (daily high price – daily low price) / closing price. *Pilot* is a dummy variable that equals 0 if the trading date is during the pre-Pilot period (i.e., before October 3, 2016) and 1 if the trading date is during the Pilot period (i.e., after October 31, 2016). *TestGroup 1* is a dummy variable that equals 1 if a stock is in Test Group 1 and 0 otherwise; *TestGroup 2* is a dummy variable that equals 1 if a stock is in Test Group 2 and 0 otherwise; and *TestGroup 3* is a dummy variable that equals 1 if a stock is in Test Group 3 and 0 otherwise. The interaction terms, *Pilot* × *TestGroup 1, Pilot* × *TestGroup 2,* and *Pilot* × *TestGroup 3*, are constructed by multiplying the *Pilot* dummy with the three Test-Group dummy variables. The last 3 rows of the table (*G1 vs. G2*, *G1 vs. G3*, and *G2 vs. G3*) present the differences among the coefficients on *Pilot* × *TestGroup 1, Pilot* × *TestGroup 2,* and *Pilot* × *TestGroup 3* and *t*-statistics that measure the normalized distance between these differences and zero. Control variables include: the average firm closing stock price (*Price)* and market capitalization (*MktCap*) during the pre-Pilot period, value weighted daily market returns (*MktReturn*), the daily price volatility of the SPY (*SPYvolatility*), the daily opening value of the VIX volatility index (*VIX*), and month indicator variables to control for time effects. Please refer to Appendix B for the detailed variable definitions. Numbers in parentheses are the t-statistics. *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

	(1)	(2)
Dependent Variables	Log(Volume $) (CRSP)	Volatility (CRSP)
Pilot × TestGroup 1	-0.03728 (-1.12)	0.00108* (1.87)
Pilot × TestGroup 2	-0.00139 (-0.04)	0.00113** (1.99)
Pilot × TestGroup 3	-0.03906 (-1.20)	0.00136** (2.50)
Pilot	0.23700*** (11.99)	0.00367*** (10.41)
Month dummies	Yes	Yes
TestGroup dummies Controls	Yes Yes	 Yes
R2	0.47	0.1
N	384,627	384,188
Tests on interaction terms	Yes	
G1 vs. G2	0.03588 (0.83)	0.00006 (0.08)
G1 vs. G3	-0.00178 (-0.04)	0.00028 (0.41)
G2 vs. G3	-0.03767 (-0.88)	0.00023 (0.33)

Table 6. Difference-in-Differences Regressions of Price Efficiency

This table presents the difference-in-differences analysis to investigate how the tick size change alters the price efficiency of stocks in the Test Groups compared to stocks in the Control Group. The regression specification is given by:

$$Price\ Efficiency_{i,t} = \beta_0 Pilot + \beta_1 TestGroup1 + \beta_2 TestGroup2 + \beta_3 TestGroup3 + \beta_4 Pilot \times TestGroup1 + \beta_5 Pilot \times TestGroup2 + \beta_6 Pilot \times TestGroup3 + \beta_7 Controls + \varepsilon_{i,t},$$

where *Price Efficiency*$_{i,t}$ represents several price efficiency measures such as *Rho_FAC*, *VR_FAC*, and *R2_FAC*. *Rho_FAC* is the first-order midpoint return autocorrelations for each stock-day. *VR_FAC* is the variance ratio measure defined in Appendix A of Comerton-Forde and Putniņš (2015). *R2_FAC* is an intraday version of Hou and Moskowitz's (2005) Price Delay measure, capturing the extent to which *lagged* market returns predict a stock's midquote returns. *Pilot* is a dummy variable that equals 0 if the trading date is during the pre-Pilot period (i.e., before October 3, 2016) and 1 if the trading date is during the Pilot period (i.e., after October 31, 2016). *TestGroup 1* is a dummy variable that equals 1 if a stock is in Test Group 1 and 0 otherwise; *TestGroup 2* is a dummy variable that equals 1 if a stock is in Test Group 2 and 0 otherwise; and *TestGroup 3* is a dummy variable that equals 1 if a stock is in Test Group 3 and 0 otherwise. The interaction terms, *Pilot* × *TestGroup 1, Pilot* × *TestGroup 2,* and *Pilot* × *TestGroup 3*, are constructed by multiplying the *Pilot* dummy with the three Test-Group dummy variables. The last 3 rows of the table (*G1 vs. G2*, *G1 vs. G3*, and *G2 vs. G3*) present the differences among the coefficients on *Pilot* × *TestGroup 1, Pilot* × *TestGroup 2,* and *Pilot* × *TestGroup 3* and *t*-statistics that measure the normalized distance between these differences and zero. Control variables include: the average firm closing stock price (*Price)* and market capitalization (*MktCap*) during the pre-Pilot period, value weighted daily market returns (*MktReturn*), the daily price volatility of the SPY (*SPYvolatility*), the daily opening value of the VIX volatility index (*VIX*), and month indicator variables to control for time effects. Please refer to Appendix B for the detailed variable definitions. Numbers in parentheses are the t-statistics. *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

	(1)	(2)	(3)
Dependent Variables	RHO_FAC (TAQ)	VR_FAC (TAQ)	R2_FAC (TAQ)
Pilot × TestGroup 1	0.00214 (1.12)	0.02831*** (9.06)	0.07779*** (10.47)
Pilot × TestGroup 2	0.00179 (0.95)	0.02864*** (8.73)	0.08650*** (10.40)
Pilot × TestGroup 3	-0.00024 (-0.13)	0.0279*** (8.70)	0.08034*** (10.51)
Pilot	-0.01324*** (-10.73)	0.04474*** (37.94)	0.04243*** (15.36)
TestGroup dummies	Yes	Yes	Yes
Month dummies	Yes	Yes	
Controls	Yes	Yes	Yes
R2	0.05	0.82	0.36
N	376,300	378,120 Yes	377,593
Test on interaction term			
G1 vs. G2	-0.00035 (-0.15)	0.00033 (0.08)	0.00871 (0.81)
G1 vs. G3	-0.00238 (-1.02)	-0.0004 (-0.10)	0.00255 (0.25)
G2 vs. G3	-0.00203 (-0.88)	-0.00074 (-0.17)	-0.00616 (-0.57)

Table 7. Regressions for Stocks Split by Average Quoted Spreads Less than or Greater than Five Cents

We compute the average dollar quoted spread for a stock during the pre-Pilot period, which we use to divide stocks into two subgroups. One group contains stocks with an average dollar quoted spread less 5 cents (< *$0.05*). The second group contains stocks with an average dollar quoted spread greater than or equal to 5 cents (>= *$0.05*).

This table presents the following difference-in-differences regressions on market quality measures across these two subsamples:

$$MarketQuality_{i,t} = \beta_0 Pilot + \beta_1 TestGroup1 + \beta_2 TestGroup2 + \beta_3 TestGroup3 + \beta_4 Pilot \times TestGroup1 + \beta_5 Pilot \times TestGroup2 + \beta_6 Pilot \times TestGroup3 + \beta_7 Controls + \varepsilon_{i,t},$$

where *Market Quality* represents several market quality measures introduced in Section 4, such as *Rel Q-spread (Pilot)*, *Rel E-spread (Pilot)*, *Rel Q-spread (TAQ)*, *Rel E-spread (TAQ)*, and *Rho_FAC*. *Pilot* is a dummy variable that equals 0 if the trading date is during the pre-Pilot period (i.e., before October 3, 2016) and 1 if the trading date is during the Pilot period (i.e., after October 31, 2016). *TestGroup 1* is a dummy variable that equals 1 if a stock is in Test Group 1 and 0 otherwise; *TestGroup 2* is a dummy variable that equals 1 if a stock is in Test Group 2 and 0 otherwise; and *TestGroup 3* is a dummy variable that equals 1 if a stock is in Test Group 3 and 0 otherwise. The interaction terms, *Pilot* × *TestGroup 1*, *Pilot* × *TestGroup 2*, and *Pilot* × *TestGroup 3*, are constructed by multiplying the *Pilot* dummy with the three Test-Group dummy variables. Control variables include: the average firm closing stock price (*Price)* and market capitalization (*MktCap*) during the pre-Pilot period, value weighted daily market returns (*MktReturn*), the daily price volatility of the SPY (*SPYvolatility*), the daily opening value of the VIX volatility index (*VIX*), and month indicator variables to control for time effects. Please refer to Appendix B for the detailed variable definitions. Numbers in parentheses are the t-statistics. *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

Panel A: Bid-Ask Spreads

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Dependent Variables	Rel Q-spread (Pilot)	Rel Q-spread (Pilot)	Rel E-spread (Pilot)	Rel E-spread (Pilot)	Rel Q-spread (TAQ)	Rel Q-spread (TAQ)	Rel E-spread (TAQ)	Rel E-spread (TAQ)
	< $0.05	>= $0.05	< $0.05	>= $0.05	< $0.05	>= $0.05	< $0.05	>= $0.05
Pilot × TestGroup 1	0.00380*** (5.80)	-0.00073 (-1.54)	0.00340*** (10.94)	0.00142*** (5.81)	18.08985*** (10.13)	-3.30589 (-1.51)	14.04277*** (10.59)	-0.13673 (-0.10)
Pilot × TestGroup 2	0.00327*** (7.29)	-0.00017 (-0.31)	0.00334*** (10.38)	0.00185*** (6.70)	17.15692*** (9.95)	-1.98054 (-0.93)	13.62884*** (10.31)	1.03848 (0.82)
Pilot × TestGroup 3	0.00325*** (7.90)	0.00019 (0.44)	0.00336*** (12.08)	0.00191*** (7.46)	16.57305*** (10.52)	0.17394 (0.08)	12.36434*** (11.77)	1.70946 (1.43)
Pilot	0.00012 (0.74)	0.0003 (1.04)	0.00036*** (6.29)	0.00062*** (6.00)	-2.68762*** (-7.17)	-4.90620*** (-3.46)	0.78568*** (2.95)	0.91279 (1.02)
Month dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
TestGroup dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R2	0.24	0.23	0.34	0.19	0.19	0.08	0.36	0.16
N	166,097	218,530	166,046	217,877	161,517	218,270	161,515	218,149

Panel B: Price Efficiency

	(9)	(10)	(11)	(12)	(13)	(14)
Dependent Variables	Rho_FAC (TAQ)	Rho_FAC (TAQ)	VR_FAC (TAQ)	VR_FAC (TAQ)	R2_FAC (TAQ)	R2_FAC (TAQ)
	< $0.05	>= $0.05	< $0.05	>= $0.05	< $0.05	>= $0.05
Pilot × TestGroup 1	0.01029*** (3.79)	-0.00481* (-1.88)	0.03531*** (7.74)	0.02212*** (5.72)	0.14717*** (12.02)	0.02347*** (3.49)
Pilot × TestGroup 2	0.00672*** (2.36)	-0.0022 (-0.97)	0.04019*** (8.17)	0.02236*** (5.76)	0.17482*** (11.85)	0.02985*** (4.64)
Pilot × TestGroup 3	0.00914*** (3.59)	-0.00744*** (-2.89)	0.03963*** (8.67)	0.01853*** (4.72)	0.16888*** (13.84)	0.0133** (2.15)
Pilot	-0.02098*** (-12.49)	-0.00748*** (-4.35)	0.04440*** (24.51)	0.04441*** (29.31)	0.05602*** (11.60)	0.03206*** (9.90)
Month dummies	Yes	Yes	Yes	Yes	Yes	Yes
TestGroup dummies	Yes	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes	Yes
R2	0.02	0.07	0.82	0.84	0.39	0.36
N	160,713	215,587	160,696	217,424	160,508	217,085

Panel C: Market Depth

	(15)	(16)	(17)	(18)	(19)	(20)
Dependent Variables	Log(NBBO Dollar Depth) MIDAS	Log(NBBO Dollar Depth) MIDAS	Log(Depth_1) MIDAS	Log(Depth_1) MIDAS	Log(Depth_3) MIDAS	Log(Depth_3) MIDAS
	< $0.05	>= $0.05	< $0.05	>= $0.05	< $0.05	>= $0.05
Pilot × TestGroup 1	1.43895***	0.83197***	0.04859	-0.00643	0.26441***	0.09051**
	(32.00)	(20.70)	(1.01)	(-0.18)	(6.30)	(2.42)
Pilot × TestGroup 2	1.48292***	0.83029***	0.09466	0.00265	0.33163***	0.10696***
	(25.41)	(28.40)	(1.54)	(0.11)	(5.92)	(3.80)
Pilot × TestGroup 3	1.66560***	0.84771***	0.16058***	0.01614	0.43894***	0.11280***
	(36.88)	(22.13)	(3.41)	(0.46)	(9.97)	(3.17)
Pilot	0.22145***	0.22854***	0.06090**	0.14801***	-0.01763	0.05761***
	(10.10)	(15.20)	(2.45)	(9.06)	(-0.77)	(3.43)
Month dummies	Yes	Yes	Yes	Yes	Yes	Yes
TestGroup dummies	Yes	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes	Yes
R2	0.61	0.57	0.33	0.45	0.32	0.44
N	166,092	218,537	161,443	218,272	161,443	218,272

Panel D: Volume and Volatility				
	(21)	(22)	(23)	(24)
Dependent Variables	Log(Volume $) CRSP	Log(Volume $) CRSP	Volatility CRSP	Volatility CRSP
	< $0.05	>= $0.05	< $0.05	>= $0.05
Pilot × TestGroup 1	-0.01321	-0.03013	0.00314***	-0.00113*
	(-0.27)	(-0.70)	(3.47)	(-1.68)
Pilot × TestGroup 2	-0.0215	0.02534	0.00280***	0.00005
	(-0.45)	(0.50)	(3.05)	(0.07)
Pilot × TestGroup 3	-0.00003	-0.0546	0.00391***	-0.0006
	(0.00)	(-1.24)	(5.07)	(-0.82)
Pilot	0.23969***	0.24731***	0.00443***	0.00299***
	(8.56)	(9.11)	(9.03)	(6.20)
Month dummies	Yes	Yes	Yes	Yes
TestGroup dummies	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes
R2	0.53	0.52	0.32	0.28
N	166,097	218,530	166,093	218,095

Table 8. Regressions of Effective Spreads by Order Sizes

This table presents the following difference-in-differences regressions of effective spreads across different order sizes:

$$Rel\ ESpread_{i,t} = \beta_0 Pilot + \beta_1 TestGroup1 + \beta_2 TestGroup2 + \beta_3 TestGroup3 + \beta_4 Pilot \times TestGroup1 + \beta_5 Pilot \times TestGroup2 + \beta_6 Pilot \times TestGroup3 + \beta_7 Controls + \varepsilon_{i,t},$$

where *Rel E-spread (Pilot)* is the relative effective bid-ask spread from the Pilot data. *Pilot* is a dummy variable that equals 0 if the trading date is during the pre-Pilot period (i.e., before October 3, 2016) and 1 if the trading date is during the Pilot period (i.e., after October 31, 2016). *TestGroup 1* is a dummy variable that equals 1 if a stock is in Test Group 1 and 0 otherwise; *TestGroup 2* is a dummy variable that equals 1 if a stock is in Test Group 2 and 0 otherwise; and *TestGroup 3* is a dummy variable that equals 1 if a stock is in Test Group 3 and 0 otherwise. The interaction terms, *Pilot* × *TestGroup 1, Pilot* × *TestGroup 2,* and *Pilot* × *TestGroup 3*, are constructed by multiplying the *Pilot* dummy with the three Test-Group dummy variables. We estimate these regressions for each order size subsample. According to the Pilot plan, *Order size 0* means the original order size is less than 100 shares; *Order size 1* means the original order size is between 100 to 499 shares; *Order size 2* means the original order size is between 500 to 1,999 shares; *Order size 3* means the original order size is between 2,000 to 4,999 shares; *Order size 4* means the original order size is between 5,000 to 9,999 shares; *Order size 5* means the original order size is greater than 10,000 shares. Control variables include: the average firm closing stock price (*Price)* and market capitalization (*MktCap*) during the pre-Pilot period, value weighted daily market returns (*MktReturn*), the daily price volatility of the SPY (*SPYvolatility*), the daily opening value of the VIX volatility index (*VIX*), and month indicator variables to control for time effects. Please refer to Appendix B for the detailed variable definitions. Numbers in parentheses are the t-statistics. *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent Variables	Rel E-spread (Pilot)	Rel E-spread (Pilot)	Rel E-spread (Pilot)	Rel E-spread (Pilot)	Rel E-spread (Pilot)	Rel E-spread (Pilot)
	Order size 0	Order size 1	Order size 2	Order size 3	Order size 4	Order size 5
Pilot × TestGroup 1	0.00254*** (12.20)	0.00245*** (13.38)	0.00251*** (12.57)	0.00200*** (9.13)	0.00237*** (8.18)	0.00258*** (5.90)
Pilot × TestGroup 2	0.00251*** (11.80)	0.00241*** (13.84)	0.00245*** (12.35)	0.00182*** (9.03)	0.00231*** (8.72)	0.00267*** (6.78)
Pilot × TestGroup 3	0.00234*** (13.53)	0.00258*** (15.18)	0.00266*** (14.14)	0.00195*** (10.83)	0.00254*** (10.52)	0.00290*** (8.10)
Pilot	0.0003*** (3.65)	0.00015*** (3.60)	0.00027*** (3.74)	0.00037*** (4.50)	0.00022** (2.21)	0.00032* (1.82)
Month dummies	Yes	Yes	Yes	Yes	Yes	Yes
TestGroup dummies	Yes	Yes	Yes	Yes	Yes	Yes
Controls	Yes	Yes	Yes	Yes	Yes	Yes
R2	0.11	0.23	0.14	0.16	0.16	0.18
N	380,049	382,461	361,832	274,584	174,615	104,632

A. The Implementation Dates of the Tick Size Pilot Program

This table details the total number of stocks trading under the increased tick size in each of the Test Groups during the implementation period of the Tick Size Pilot Program in October 2016.

Groups		Oct 3	Oct 10	Oct 17	Oct 24	Oct 31
Control Group	Will be quoted and trade at their current $0.01 tick size increment.					
Test Group 1 (Quote Increment)	Will be quoted in $0.05 increments, but will continue to trade at their current price increment	5 Symbols	100 Symbols	400 Symbols		
Test Group 2 (Quote + Trade Increment)	Will be quoted and trade in $0.05 minimum increments.	5 Symbols	100 Symbols	400 Symbols		
Test Group 3 (Quote + Trade Increment + Trade-At Requirement[65])	Will adhere to the requirements of the second Test Group, but will also be subject to a "trade-at" requirement.			5 Symbols	100 Symbols	400 Symbols

Note: The list of Test Group stocks can be found at http://www.finra.org/sites/default/files/Tick_Pilot_Test_Group_Assignments.txt.

<u>Other institutional details</u>:

Stocks to be included in the Pilot Program: Common stocks only

- **Capitalization:** under $3 billion in market capitalization on the last day of the Measurement Period[66]
- **Volume:** under 1 million shares average daily volume during the Measurement Period.
- **Price:** above $2 per share on the last day of the Measurement Period and above $2 VWAP during the Measurement Period (see “the Plan”).

[65] According to the Plan, the trade-at prohibition (1) prevents a trading center that was not quoting from price-matching protected quotations and (2) permits a trading center that was quoting at a protected quotation to execute orders at that level, but only up to the amount of its displayed size. Here, "Trade-at" means the execution by a trading center of a sell order for a Pilot Stock at the price of a protected bid or the execution of a buy order for a Pilot Stock at the price of a protected offer during Regular Trading Hours. Please see pages 18-20 of the Plan for examples illustrating trade-at prohibition.

[66] See supra note 25.

B. Data Filtering

We apply filters to some of the data to reduce the influences of data errors and extreme observations. For the Tick Size Pilot Data, we eliminate the following observations from the Appendix B.I. (Market Quality Statistics) data: (i) observations outside of regular trading hours; (ii) observations with Tick Size Special Handling Indicator equal to “Y”, (iii) observations with Multiday Order Indicator equal to “Y”, and (iv) observations with order type code greater than 14 (that is, we only keep market order and limit order observations). We winsorize the Pilot data variables at 0.1% and 99.9% levels to remove outliers. We filter the TAQ data following Holden and Jacobsen (2014).

C. Variable Definitions

Variables	Definition	Data Sources
Rel Q-spread (Pilot)	Relative quoted bid-ask spread from the Pilot data defined as the share-weighted average of "Share Weighted Average NBBO Spread at the Time of Order Receipt" (WA_NBBO_SPD) for a stock-day observation. It is scaled by the daily volume-weighted average price (VWAP) based on the NBBO midquote.	Pilot data
Rel E-spread (Pilot)	Relative effective bid-ask spread from the Pilot data defined as share-weighted average of "Average Effective Spread for Executions for Orders" (WA_EFF_SPD) for a stock-day observation (only applies to Order Types 10 and 11 with no Tick Size Special Handling). It is scaled by the daily volume-weighted average price (VWAP) based on trade prices.	Pilot data
Rel Q-spread (TAQ)	Time-weighted daily average of relative quoted bid-ask spread for a stock-day observation. The relative quoted bid-ask spread is calculated using the difference between the log of the NBO and the log of the NBB.	TAQ data

Rel E-spread (TAQ)	Share-weighted daily average of relative effective bid-ask spread for a stock-day observation. The relative effective bid-ask spread is defined as the absolute value of double the difference between the log trade price and the log NBBO midquote before the trade took place.	TAQ data
Rel R-spread (TAQ)	Share-weighted daily average of relative realized spread for a stock-day observation. The relative realized spread is the signed difference between the log price paid for a transaction and the log NBBO midquote observed five minutes after the execution takes place. A trade initiated by a market buy order has a sign of 1 and a trade initiated by a market sell order has a sign of -1.	TAQ data
Rel Price Impact (TAQ)	Share-weighted daily average of price impact for a stock-day observation. The relative price impact is the signed difference between the log NBBO midquote at the time right before the trade took place and the log NBBO midquote observed five minutes after the trade took place. A trade initiated by a market buy order has a sign of 1 and a trade initiated by a market sell order has a sign of -1.	TAQ data
Log(NBBO Dollar Depth) (MIDAS)	The natural logarithm of the stock day average of the cumulative dollar value of limit order book depth that is displayed across all exchanges at the NBBO.	MIDAS
Log(Depth_1) (MIDAS)	The natural logarithm of Depth_1, which is the stock day average of the cumulative dollar value of limit order book depth that is displayed across all exchanges within five cents of the NBBO.	MIDAS
Log(Depth_3) (MIDAS)	The natural logarithm of Depth_3, which is the stock day average of the cumulative dollar value of limit order book depth that is displayed across all exchanges within 15 cents of the NBBO.	MIDAS

Rho_FAC	The first-order midpoint return autocorrelations for each stock-day. Please refer to Appendix A of Comerton-Forde and Putniņš (2015) for detailed definitions of Rho_FAC, VR_FAC, and R2_FAC.	TAQ data
VR_FAC	This is the variance ratio measure defined in Appendix A of Comerton-Forde and Putniņš (2015).	TAQ data
R2_FAC	This is an intraday version of Hou and Moskowitz's (2005) Price Delay measure, capturing the extent to which *lagged* market returns predict a stock's midquote returns. It is defined in Appendix A of Comerton-Forde and Putniņš (2015).	TAQ data
Log(Volume $)	The natural logarithm of the dollar trading volume of a stock on a given date. Defined as *Price* times CRSP daily shares traded.	CRSP database
Volatility	Stock price volatility of a stock on a given date, defined as (daily high price – daily low price) / closing price.	CRSP database
Control Variables		
Price	The average closing price (or the average of closing bid and ask price if there was no closing trade) for a stock during the Pre-Pilot Period.	CRSP database
MktCap	The average market capitalization, defined as Closing Price times the number of shares outstanding, for a stock during the Pre-Pilot Period.	CRSP database
MktReturn	Value-weighted market returns (VWRETD).	CRSP database
VIX	The daily opening Chicago Board Options Exchange (CBOE) volatility index, which is a measure of the *implied* volatility of S&P 500 index options.	CBOE website
SPYvolatility	The price volatility of SPY on a given date, defined as (daily high price – daily low price) / closing price. SPY is an ETF designed to track the S&P 500 stock market index.	CRSP database