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TICK SIZES IN ILLIQUID ORDER BOOKS

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Tick sizes in illiquid order books

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Abstract

I assess the causal impact of increasing the tick size on stock liquidity and trading volume in illiquid stocks. Using a regression discontinuity design at the Oslo Stock Exchange, I find that increasing the tick size has no impact on the transaction costs, order book depths, or trading volumes of illiquid stocks. These findings contradict recent theoretical predictions in the market microstructure literature as well as proposals by lawmakers in the United States to increase the tick size for illiquid stocks.

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Introduction

Stock exchanges fine-tune their market designs to improve liquidity. A much-used strategy over the last two decades has been to reduce the tick size — the smallest price increment on an exchange.[1] However, the impact of tick size reductions on stock liquidity is uncertain. On the one hand, a smaller tick size can enhance price competition among investors and lead to narrower bid-ask spreads. On the other hand, a smaller tick size makes it easier to undercut other investors' limit orders, which can discourage investors from providing liquidity with limit orders. This ambiguity has created strong demand among policy makers for evidence on the impact of tick sizes on stock liquidity, in particular for illiquid stocks.[2]

The purpose of this paper is to assess the causal impact of tick sizes on stock liquidity and trading volume for both liquid and illiquid stocks. Buti et al. (2015) show theoretically that tick size reductions can decrease liquidity in illiquid stocks but increase liquidity in liquid stocks. The mechanism behind their result is that tick size reductions for liquid stocks enhance price competition, resulting in narrower bid-ask spreads and increased aggregate depth (though depth at the best bid-ask declines). However, as traders switch from market orders to limit orders, total trading volume declines. For illiquid stocks, in contrast, Buti et al. (2015) show that the costs of discouraging liquidity supply dominate the benefits of enhancing price competition, such that a reduction in the tick size reduces order book depth and widens the bid-ask spread, while total trading volume increases.

A regression discontinuity design at the Oslo Stock Exchange (OSE) allows for clean identification of the effect of tick sizes on stock liquidity and trading volume. I exploit that tick sizes at the OSE are determined as a function of the stock price — higher priced stocks have larger tick sizes. Comparing stocks that are priced marginally above tick size price thresholds to stocks that are priced marginally below the price thresholds in a regression discontinuity design allows for causal inference.

[1] For example, tick sizes in the United States have gradually declined over the past decades. The American Stock Exchange (AMEX) reduced its tick size for selected stocks to $1/16 in 1992, and further applied this tick size to all AMEX stocks in 1997. Also in 1997, the New York Stock Exchange and NASDAQ implemented $1/16 tick sizes. Decimal pricing was phased in from 2000, and was fully implemented by 2001.

[2] As a means to learn more about the effects of tick sizes on the liquidity in small and illiquid securities, policy makers in the United States have recently initiated a large-scale experimental program that has increased the tick size for 1200 randomly chosen small capitalization securities. The 'Tick Size Pilot Program' officially commenced in late 2016 and will last for a two-year period.

I use the regression discontinuity design to explore the causal effect of tick sizes on the liquidity in liquid stocks. To this end, I explore a long sample period (2008 – 2011) with exogenous variation in the tick size for the most liquid stocks at the OSE — the 25 stocks in the OBX index. I find that increasing the tick size for this population of liquid stocks leads to wider spreads and increased order book depth at the best bid and ask. Moreover, the regression discontinuity design shows a weak and potentially time-varying positive impact of increasing the tick size on trading volume. These results are broadly consistent with the theoretical predictions in Buti et al. (2015) for liquid order books.

To explore the effects of tick size changes for illiquid stocks, I apply the regression discontinuity design to a sample comprising a large number of both liquid and illiquid stocks at the OSE (all non-OBX index stocks). For this population of stocks, there are more than 2300 exogenous tick size changes distributed across 158 unique stocks in the period 2008 – 2011, allowing for precise estimation of both average treatment effects and effect heterogeneity. I find that the average causal effect of increasing the tick size for the combined sample of liquid and illiquid stocks is to widen bid-ask spreads and to increase order book depth. However, the average effect is mostly accounted for by the most liquid stocks (top 40% of the liquidity distribution), whose liquidity responds heavily to tick size changes. In contrast, I find no impact of tick size changes on spread measures of liquidity, order book depth, volatility, or trading volume for stocks in the bottom 60% of the liquidity distribution.

This paper connects to several academic debates. First, my results connect to the already voluminous empirical literature on the impact of tick sizes on measures of stock liquidity (for a recent survey of the literature, see SEC 2012). The existing empirical literature has mostly focused on one-off tick size reforms where identification is difficult.[3] Similar to Buti et al. (2015), I exploit exogenous variation in tick sizes in a regression discontinuity design for causal inference. In line with Buti et al. (2015), I find that the average effect of increasing the tick size is to widen spreads and to increase order book depth.

Second, I contribute to the emerging empirical literature which explores whether tick

[3]Much of the existing literature is based on before-and-after variation in tick sizes surrounding regulatory reforms, which does not allow for a separation of the effect of tick sizes from confounding trends (e.g., Goldstein and Kavajecz 2000, Ronen and Weaver 2001). Some papers attempt to adjust for confounding trends by estimating the effects of tick size reforms net of the trend in a control sample of unaffected stocks (e.g., Bacidore et al. 2003, Chakravarty et al. 2004). This approach captures the causal effect of tick sizes only under the strict assumption that reform stocks and control stocks follow the same trends in the absence of tick size reform.

sizes affect liquid and illiquid stocks differently. Buti et al. (2015) build a theoretical model which predicts opposite effects of tick size changes for liquid and illiquid stocks, and test their predictions using data from the London Stock Exchange, NYSE, and Nasdaq. However, as the authors themselves point out, their data are ill-suited for testing predictions related to illiquid order books as most of their sampled stocks are, in fact, liquid.[4] In contrast, the Oslo Stock Exchange comprises a wide range of both liquid and illiquid stocks, which allows me to test the causal impact of tick size changes in both liquid and illiquid trading environments. Doing so, I find that the quality of trading in liquid stocks responds heavily to tick size changes while the quality of trading in illiquid stocks is unaffected by tick size changes.[5]

Finally, my research can provide guidance to policy makers in the United States who are currently considering tick sizes as a tool to improve the quality of trading in illiquid securities (see footnote 2). My causal estimates suggest that other market design tools than tick sizes are needed if the object is to improve the quality of trading in illiquid stocks.

The paper proceeds as follows. Section 1 provides institutional background on the determination of tick sizes at the Oslo Stock Exchange; Section 2 describes the data; Section 3 estimates a benchmark before-and-after event study specification; Section 4 describes the empirical identification strategy; Section 5 presents the main results; and Section 6 discusses the results and concludes.

[4]Buti et al. (2015) test their theoretical predictions using three data samples and two different empirical designs; a regression discontinuity design to exploit a price-based tick size for liquid securities at the London Stock Exchange; a regression discontinuity design to exploit that the tick size for stocks in the United States increases from \$0.0001 to \$0.01 as they cross the \$1 price threshold; and a Fama-MacBeth approach to explore how changes in the relative tick size affect a sample of 180 NYSE and Nasdaq stocks. Among these data samples, only U.S. securities surrounding the \$1 price threshold can plausibly be defined as illiquid. Nevertheless, Buti et al. (2015) use their estimates from the low-priced U.S. sample to shed light on theoretical predictions concerning liquid stocks. A potential explanation for why the authors choose not to explore in greater detail how the effect of crossing the \$1 price threshold depends on initial stock liquidity, is that their sample of low-priced U.S. stocks only comprises 20 unique securities.

[5]In other empirical work, O'Hara et al. (2015) explore whether changes to the relative tick size affect stocks in a one-tick environment (the bid-ask spread is equals the tick size) and stocks in multi-tick environments differently. They show that in the one-tick environment, an increase in the relative tick size leads to more trading volume and increased order book depth. In contrast, in the multi-tick environment an increase in the relative tick size leads to less trading volume and less order book depth. My results connect to O'Hara et al. (2015) since my classification of liquid and illiquid stocks captures a similar separation between one-tick and multi-tick trading environments. In particular, the most liquid stocks in my sample tend to trade in (or close to) one-tick environments while the least liquid stocks tend to trade in multi-tick environments. Unlike O'Hara et al. (2015), I find no effect of tick size changes in multi-tick environments but a strong effect of tick size changes in one-tick environments.

1 Institutional background

This section gives an overview of the market design and institutional setting of the Oslo Stock Exchange before it describes in detail how tick sizes are determined at the Oslo Stock Exchange.

1.1 Overview: The Oslo Stock Exchange

The OSE operates a fully electronic limit order book, and has done so since January 1999. The OSE order book allows conventional limit orders, market orders, iceberg orders and various other common order types. Order placements at the OSE follow price-time priority — orders are first sorted by their price and then, in case of equality, by the time of their arrival.[6] The trading day at the OSE comprises three separate trading sessions: an opening call period, a continuous trading period, and a closing call period. In late 2012, the continuous trading session was shortened from 09:00 – 17:20 to 09:00 – 16:20. Call auctions may be initiated during continuous trading if triggered by price monitoring or to restart trading after a trading halt. Meling (2016) provides details on the market transparency at the OSE.

Competing stock exchanges offer trading in some, but not all, of the 200 − 300 stocks listed at the OSE. In 2008, competing stock exchanges offered trading only in the largest and most liquid stocks at the OSE, before gradually expanding their selection of tradable stocks. For example, Chi-X, a so-called multilateral trading facility (MTF), initially offered trading in only the five largest OSE stocks (Norsk Hydro ASA, Renewable Energy Corp. A/S, StatoilHydro ASA, Telenor ASA, and Yara International ASA). At the time of writing in 2016, Chi-X offers trading in more than 50 OSE products. Likewise, Turquoise initially opened trading in 28 OSE stocks in 2008 but has since greatly expanded its selection to include more than 150 OSE products. For more details on the exchange competition for order flow in OSE listed products, see Meling and Ødegaard (2016).

[6] After the sample period I study, the OSE has adopted a price-visibility-time priority scheme where for price equality displayed orders are given preference over hidden orders. Traders also have the option to preferentially trade with themselves before trading with other traders. Such orders execute according to price-counterparty-visibility-time.

1.2 Tick sizes at the Oslo Stock Exchange

Tick sizes at the OSE are determined as a function of stock prices — stocks with higher prices have larger tick sizes. When prices cross a pre-specified price threshold from below (above) the tick size increases (decreases) instantly and automatically. I refer to the combined set of stock price thresholds that determine tick sizes as a 'tick size schedule.'

Over the last decade, there have been several changes to the tick size schedules at the OSE. Table 1 summarizes all the tick size schedules used by the OSE in the period 2003 – 2012. From June 2003, all stocks at the OSE shared the same 'four-step' tick size schedule with price thresholds at 10NOK, 50NOK, 150NOK, and 1000NOK. In September 2006, the OSE introduced separate tick size schedules for its large-cap stocks and small-cap stocks. Stocks listed on the OBX index, which contains the 25 most traded stocks at OSE, are defined by the OSE as 'large caps.'[7]

The tick size schedules introduced in September 2006 were maintained until the Summer of 2009, when a 'tick size war' erupted between the OSE and several competing stock exchanges (the events of this tick size war are described in detail by Meling and Ødegaard 2016). Beginning on June 1, 2009, Chi-X significantly reduced the tick size for its selection of OSE listed stocks, quickly followed by Turquoise (June 8) and BATS Europe (June 15). On July 6, 2009, the OSE responded by reducing the tick size for all OBX index to a flat 0.01NOK. On August 31, 2009, all stock exchanges agreed on and implemented a shared pan-European tick size schedule for OBX index stocks, mandating much smaller tick sizes than before the tick size war.

2 Data

In this section, I describe the data sources used in this study and define measures of stock liquidity. Finally, I provide summary statistics from the data sample.

[7] The OBX index is aimed to be a highly liquid composition of shares that reflects the Oslo Stock Exchange investment universe. The stock composition of the OBX is revised twice a year (end of June and December). Stocks are selected for the OBX list based on cumulative trading volume in the six months leading up to a new OBX composition. For trading at the OSE, the OBX shares tend to have different rules than the other shares listed at the OSE (see for example Meling 2016).

2.1 Data sources

I employ two datasets to inform about the impact of changing the tick size on stock market quality at the Oslo Stock Exchange. First, I collect daily frequency data on all common stock at the Oslo Stock Exchange from *Børsprosjektet* at the Norwegian School of Economics (similar to CRSP). The data covers the period January 2003 - December 2011. This dataset holds information on opening and closing prices, daily price dispersion (highest and lowest prices), measures of trading volume (in NOK and in shares), end-of-day bids and asks, and OBX and OSEBX index constituency indicators. I generate tick sizes from these data on a daily level based on information on end-of-day prices and the prevailing tick size schedule for a given stock (Table 1).

Second, to explore how tick sizes affect measures of stock liquidity and trading costs, I use the ThomsonReuters Tick History (TRTH) Database. The TRTH database contains trade-and-quote data for OSE listed stocks across all European equity market places, and is available in the time period 2008 – 2011. For lit exchanges (where the limit order book is displayed), the TRTH provides information on the ten best levels of the bid and ask side of the limit order book. The ThomsonReuters data also includes information on over-the-counter trading of OSE shares, by including trades reported by Markit BOAT (a MiFID-compliant trade reporting facility).

2.2 Sample selection

In the main empirical analysis (Section 5), I place three restrictions on the data. First, I exclude from the overall data sample (January 2008 – December 2011) observations in the time period June 2009 — August 2009, a highly disruptive period where competing stock exchanges challenged OSE market shares by reducing tick sizes for OSE listed stocks (see Meling and Ødegaard 2016).

Second, I restrict the sample based on stock prices. While the OSE tick size schedules provide exogenous variation in tick sizes up to the 1000NOK price threshold, there is only sufficient variation around the lower-priced thresholds. To illustrate this point, Figure 1 plots the frequency of observations at each stock price level for both non-OBX and OBX index stocks. In order to have sufficient data surrounding each of the tick size thresholds, I remove from both the OBX and non-OBX samples all stocks whose price exceeds 200NOK at any point in time throughout the sample period $2008 - 2011$. Furthermore, the tick size price thresholds for low-priced OBX stocks are closely spaced, especially in the time period September $2009 - 2011$, which reduces the amount of data available around each threshold (see Table 1). To circumvent this issue, I remove from the OBX sample stocks whose price at any point in time during $2008 - 2011$ falls below 5NOK.

Notice, however, that the sample restrictions described above do not apply to the benchmark before-and-after analysis in Section 3. In the before-and-after analysis, I use data from the time period June 2009 — August 2009 and place no price-based restrictions on the data.

2.3 Variable construction

I use the ThomsonReuters Tick History database to compute a variety of stock liquidity measures. To capture the transaction cost dimension of stock liquidity, I compute two spread measures of liquidity. First, the relative spread is defined as the difference between the current best bid and ask divided by the quote midpoint. The relative spread is updated whenever the limit order book is updated, and is calculated as the average of these estimates throughout the trading day.

Second, the realized spread captures the gross revenue to liquidity suppliers after accounting for adverse price movements following a trade. The 5-minute realized spread for transaction j in stock i is given by $q_{ji}(p_{ji} - m_{i,j+5\text{min}})/m_{ji}$, where q_{ji} is an indicator variable that equals $+1$ for buyer-initiated trades and -1 for seller-initiated trades; p_{ji} is the trade price; and $m_{i,j+5\text{min}}$ is the quote midpoint 5 minutes after the j'th trade. To determine whether an order is buyer or seller initiated, the transaction price is compared to the previous quote midpoint — if the price is above (below) the midpoint it is classified as a buy (sell). The daily realized spread is computed as the average across all transactions during the trading day.

The depth dimension of stock liquidity is captured by calculating the sum of pending trading interest at the best bid and ask prices, measured in monetary terms (NOK). My measure of order book depth is updated whenever the limit order book is updated, and averaged across all order book states throughout the trading day. To proxy for the noise in the price process, I estimate realized volatility as the second (uncentered) sample moment of the within-day 10-minute stock returns.

Since the liquidity measures described above are based on within-day data while tick sizes in my setting are based on end-of-day stock prices, regressions of liquidity outcomes on tick sizes may be affected by measurement error. For example, a stock may cross a tick size price threshold during the trading day and cross back below the price threshold before the close. The end-of-day tick size would not reflect these price crossings but the liquidity measures might. Such measurement error, however, should only serve to attenuate the regression discontinuity estimates.

2.4 Summary statistics

Table 2 presents summary statistics of the trading in both small-cap and large-cap stocks at the OSE. All summary statistics are based on the Reuters order-level data from the time period $2008-2011$. The table shows that trading in small-cap stocks at the OSE differ from large-cap trading in several ways. First, there are considerable differences in stock liquidity, measured both in transaction costs and in order book depth. For example, the relative spread is (on average) 369.42 basis points (bps.) in small-caps and only 29.47 bps. in large-caps. Similarly, the realized spread is 59.74 bps. and 2.21 bps for small and large-caps, respectively. Large-cap order books are more than twice as deep as small-cap order books, and the average trading volume in large-cap stocks (155 million NOK) is more than 30 times larger than the trading volume in small-cap stocks (4.77 million NOK). Perhaps as a result of the greater liquidity, price volatility in large-caps is considerably smaller than in small-caps.

Second, tick sizes, both in absolute terms and in relative ($ticksize/price$) terms, differ between liquid and illiquid stocks at the OSE. In particular, tick sizes for small-caps are larger than for large-caps even though small-cap stock prices are lower. This is because the large-cap tick size schedules mandate smaller tick sizes for any given stock price. As a consequence, the relative tick size is five times larger for small-caps than for large-caps. At the same time, the tick size appears to be a less binding constraint for small-caps than for large-caps. For example, the 'ticks-per-quoted-spread', a common measure of how binding the tick size is, averages 3.69 for the large-cap sample and 10.44 for small-caps. Thus, the likelihood of the tick size being a binding constraint on the bid-ask spread differs considerably between the large-cap and small-cap samples.

3 Benchmark methodology: Before-and-after

To provide a benchmark for my later regression discontinuity estimates, and to replicate the methodology used in much of the existing empirical literature, I begin my empirical analysis by estimating the impact of tick size changes on stock market quality using a simple before-and-after specification. On July 6, 2009, the OSE unilaterally reduced the tick size for the 25 stocks in the OBX index to 0.01NOK. Before this date, tick sizes for OBX index stocks were determined by individual stock prices, and the stock price mandated tick sizes were typically much larger than 0.01NOK (see Table 1 for the full tick size schedules).

I estimate the impact of the July 6, 2009 tick size reduction using the standard before-and-after estimator:

$$y_{it} \quad = \quad \alpha + \beta Post_t + \epsilon_{it}, \tag{1}$$

where $Post_t = 1$ for observations after the event date July 6, 2009. Consequently, the regression coefficient β captures the difference-in-means in y_{it} before and after the event date, which is typically interpreted as a measure of the effect of the tick size change on y_{it}. I estimate equation 1 using a short sample period surrounding the event date — ten trading days before and ten trading days after the event date — to minimize the influence of confounding factors on my estimate of β.

Table 3 presents estimates from the before-and-after specification. The table shows that, in line with the existing empirical research, the OSE tick size reduction leads to tighter relative spreads (-10%, $t - stat = 2.27$) and shallower order books (-42%, $t - stat = 9.36$). Moreover, the before-and-after exercise reveals that reducing the tick size leads to less trading activity, captured by a 12% reduction in NOK trading volume ($t - stat = 2.14$). I find no impact of the tick size reduction on realized spreads or volatility.

4 Methodology

The purpose of this section is to devise an empirical methodology which can estimate the causal relationship between tick size changes and measures of stock liquidity and trading volume. In Section 3, I used a before-and-after estimator to assess the effect of a tick size reduction on stock outcomes:

$$y_{it} = \alpha + \beta Post_t + \epsilon_{it}, \tag{2}$$

where

$$Post_t = \begin{cases} 1, & \text{if } t \geq t^* \\ 0, & \text{otherwise} \end{cases} \tag{3}$$

and t^* = July 6, 2009 — the date of a tick size reduction for the most liquid stocks at the OSE. The before-and-after effect of interest is captured by the coefficient β, while the error term ϵ_{it} captures all other determinants of the outcome. The coefficient β is derived by computing the mean of y_{it} over all periods $t < t^*$, and subtracting it from the mean of y_{it} computed over *all* periods $t \geq t^*$. In Section 3, the estimates of β suggested that reducing the tick size for liquid stocks results in a reduction in both spread measures of liquidity and order book depth, and a reduction in trading volume.

The coefficient β, however, is unlikely to capture a causal relationship between tick sizes and outcomes y_{it}. The reason for this is that before-and-after estimators, in general, are notoriously susceptible to the influence of pre-existing trends and seasonal effects. The setting surrounding the July 6, 2009 tick size reduction at the OSE is no different — for example, Meling and Ødegaard (2016) point out that stock liquidity at the OSE was improving throughout the calendar year 2009 for reasons unrelated to tick size reductions, and that trading behavior at the OSE tends to be different during the Summer months even in the absence of tick size changes. As a consequence, $Post_t$ may be correlated with omitted variables that are themselves correlated with y_{it} — leading to a biased estimate of β.

The price-based tick size determination at the Oslo Stock Exchange provides a useful source of exogenous variation to overcome this endogeneity problem. Stocks that are priced marginally above a tick size price threshold are assigned to a different tick size than stocks that are priced marginally below a tick size threshold. If traders cannot (or will not) strategically manipulate prices in order to induce tick size changes, it is essentially random whether a stock is priced marginally above or marginally below a tick size threshold.[8]

The so-called regression discontinuity (RD) design can be used to exploit such quasi-

[8] Such strategic pricing behavior would most likely result in a discontinuous change in the density of price observations at the tick size price thresholds (McCrary 2008). Reassuringly, however, Figure 1 indicates that there is no excess density (or bunching) at the price levels where the tick sizes increase, suggesting an absence of price manipulation which could invalidate the empirical design.

random variation. The RD design relates discontinuities in outcomes at some 'treatment' threshold to discontinuities in the probability of treatment at the same point (see Lee and Lemieux 2010 for a survey). In the context of tick sizes at the Oslo Stock Exchange, the RD design relates discontinuities in the tick size (panel a, Figure 2) to discontinuities in outcomes at the same price levels (panel b, Figure 2). The basic idea is that stocks that are priced, for example, 49NOK are likely to provide an adequate control group for stocks that are priced 50NOK. In such a setting, differences in outcomes between stocks priced marginally above and marginally below a price threshold can be attributed to the difference in tick size that the two stocks experience.

To implement the RD approach in my empirical setting, with a discrete treatment variable of interest (as opposed to binary) and multiple treatment thresholds (as opposed to a single threshold), I employ a slightly modified version of the RD designs used by Urquiola and Verhoogen (2009) and Lacetera et al. (2012). I implement the RD design with the following regression specification:

$$y_{it} = \alpha_i + \alpha_t + \tau Ticksize_{it} + f\left(Price_{it}\right) + \varepsilon_{it} \tag{4}$$

where y_{it} is some outcome for stock i on date t; $Ticksize_{it}$ is the discrete tick size; and $f\left(Price_{it}\right)$ is a flexible function of the stock price. If specified correctly, $f\left(Price_{it}\right)$ will capture all dependence of y_{it} and $Ticksize_{it}$ on the stock price away from the tick size price thresholds, such that the coefficient τ is estimated using only the variation in the tick size that occurs at the exact stock price levels where the tick size changes (the tick size discontinuities in panel a, Figure 2). The coefficient τ can be interpreted as the causal effect of tick sizes on y_{it}, under the identifying assumption that stocks are comparable in both their observable and unobservable stock characteristics at the price thresholds.

Consistent estimation of τ requires an assumption about the functional form of the relationship between y_{it} and the stock price. The RD literature has proposed two main approaches to estimating equation 4 when the functional form of this relationship is unknown. The first approach is to restrict the sample size on either side of a treatment threshold and estimate non-parametric local linear regressions around the threshold. The second approach, in contrast, involves using all the available data and selecting a flexible parametric specification for $f\left(Price_{it}\right)$.

While the local linear regression approach is theoretically more appealing (Hahn et al. 2001, Lee and Lemieux 2010), I follow Lacetera et al. (2012) and Urquiola and Verhoogen (2009) and estimate the regression discontinuity design globally by allowing for a flexible parametric specification of $f(Price_{it})$. Following Lacetera et al. (2012), I approximate $f(Price_{it})$ with a seventh order polynomial. The reason why I choose the parametric approach instead of the non-parametric local linear approach, is that my empirical setting departs from the 'standard' RD setting since there are multiple price thresholds that determine tick sizes. Instead of treating each tick size price threshold individually with local linear regressions, for convenience, I estimate the combined impact of all the thresholds within the same regression specification. The parametric approach yields the added benefit of allowing me to utilize more of the data which may improve statistical precision.

Stock prices may be more likely to cross a tick size price threshold on days when prices are volatile. To control for the influence of market-wide movements that can induce tick size changes, I add to equation 4 a full set of time fixed effects (α_t). Moreover, to control for unobserved and unchanging characteristics of a given stock, I add a full set of stock fixed effects to equation 4 (α_i). As a consequence, the identifying variation that is captured by the τ coefficient arises from stocks that cross a tick size price threshold at least once during the sample period, either from above or below.[9]

In the appendix of this article, I expose the regression discontinuity design to several validity tests and robustness specifications. The appendix shows that the main results are fairly stable across alternative polynomial specifications of $f(Price_{it})$, and that the main results are robust to the inclusion of control variables. Finally, the appendix tests for and rejects discontinuities in y_{it} at placebo tick size price thresholds (price levels that do not affect the tick size).

In all regression specifications, standard errors are clustered at the stock-level.

[9]This is similar in spirit to the much-used difference-in-differences identification approach. The difference-in-differences estimator is measured as the change in outcomes for a treated group of stocks before and after an event relative to the corresponding change in outcomes for a control group of stocks unaffected by the event. Unlike the difference-in-differences approach, however, the regression discontinuity design in equation 4 only uses variation in outcomes that is generated on the exact dates when the tick size changes.

4.1 Summary of price threshold crossings

The identifying variation in equation 4 arises from stocks that cross tick size price thresholds either from above or below. Table 4 summarizes the occurrence of crossings of the NOK10, NOK15, NOK50, and NOK100 tick size price thresholds throughout the sample period $2008-2010$. The table reports threshold crossings separately for non-OBX and OBX index stocks. For non-OBX stocks, there are 2330 tick size threshold crossings distributed across 157 unique stocks. The most-crossed price thresholds are NOK10 and NOK15, totalling more than 800 crossings (from above and below) for each threshold. The least-crossed price threshold is, by far, NOK100 with less than 200 crossings throughout the sample period.

For the OBX sample, there are 345 crossings of the 10NOK, 15NOK, 50NOK, and 100NOK price thresholds distributed across 26 unique stocks. Notice, however, that the actual number of tick size changes for OBX index stocks is less than the 345 price threshold crossings reported in Table 4. Due to a change in the tick size schedule for OBX index stocks in September 2009, crossings of the 10NOK (15NOK) price threshold in the first (second) half of the sample period $2008-2011$ did not lead to tick size changes. In the empirical analysis, I account for the change in tick size schedules by estimating the regression discontinuity design separately for observations before and after September 2009.

5 Main results

In this section, I use a regression discontinuity design to estimate the causal impact tick size changes on the stock liquidity and trading volume at the Oslo Stock Exchange. The section begins by exploring the impact of tick size changes for liquid stocks in the OBX index, before it describes how the impact of tick sizes depends on initial stock liquidity.

5.1 Tick sizes in liquid stocks

The empirical results in Section 3 suggested that reducing the tick size for the most liquid stocks at the OSE (OBX index stocks) results in narrower bid-ask spreads, lower order book depth, and reduced trading volume. The conclusions in Section 3, however, arise from a before-and-after event study surrounding a single tick size reduction. Table 6, instead, uses the regression discontinuity design described in Section 4 to evaluate the causal impact of tick sizes on stock liquidity and trading volume for liquid stocks. The table presents estimates from the regression discontinuity design applied separately to two time periods: January 2008 – May 2009, and September 2009 – December 2011.[10]

Table 6 confirms that increasing the tick size for liquid stocks results in wider spreads and deeper order books. In the latest time period, September 2009 – December 2011, there is also weak evidence that increasing the tick size causes more trading volume. This effect, however, is not present in the earliest time period (January 2008 – May 2009), which suggests that the tick size, over time, may have become a more important factor for large-cap stock trading volume. A potential explanation for the increasingly benign impact of tick sizes on trading volume could be the recent explosion in high-frequency trading (HFT), both at the OSE (Jørgensen et al. 2016) and around the world in general. Recent empirical work by O'Hara et al. (2015) suggests that HFTs prefer to trade in large-tick size environments, since large tick sizes exacerbate the HFT speed advantage. The interaction between an increase in HFT activity and their presumed preference for large-tick trading may explain why larger tick sizes improve trading volume in the latest time period (September 2009 – December 2011) but not the earliest time period (January 2008 – May 2009).

The results in Table 6 not only validate the before-and-after estimates from Section 3; they also line up with the existing empirical tick size literature. A voluminous literature, predominantly focusing on regulatory tick size changes using before-and-after estimators, has established that increasing the tick size leads to wider bid-ask spreads and deeper order books (see for example the recent survey by the Securities and Exchange Commission 2012). My results complement the existing literature by showing that the established relationships between tick sizes, bid-ask spreads, and order book depths for liquid stocks are robust to a rigorous regression discontinuity design. Moreover, my results add to the existing empirical literature by showing a potentially time-varying relationship between tick sizes and trading volume for liquid stocks.

[10] The overall sample period (2008 – 2011) is split into two separate periods to account for the change in the tick size schedule for OBX index stocks in late August 2009. Table 1 provides detailed information on the tick size schedules used in the periods January 2008 – May 2009, and September 2009 – December 2011.

5.2 Tick sizes in illiquid stocks

Section 5.1 established a strong effect of increasing the tick size on stock liquidity for liquid stocks at the Oslo Stock Exchange. Motivated both by recent theoretical predictions by Buti et al. (2015) and by the current tick size policy debate in the United States, I turn to explore whether tick sizes affect the market quality of liquid and illiquid stocks differently. In order to estimate such cross-sectional treatment effect heterogeneity, I employ the sample of non-OBX index stocks in the period 2008 – 2010. Unlike the OBX sample, which only holds at most 25 stocks, the non-OBX sample comprises a large number of both liquid and illiquid stocks, which is a prerequisite for exploring cross-sectional heterogeneity.

I begin by assessing the average impact of increasing the tick size for the full sample of non-OBX index stocks using a regression discontinuity design and data from the time period 2008 – 2011. The bottom panel of Table 6 shows that the average effect of increasing the tick size for the full sample of non-OBX index stocks is to widen spread measures of liquidity and to improve order book depth. At the same time, I find no relationship between trading volume and tick sizes for this sample of stocks. Thus, the average effect of increasing the tick size for non-OBX stocks does not appear to differ much from the average effect of increasing the tick size for liquid stocks (top two panels of Table 6).

The average treatment effects displayed in Table 6, however, may conceal considerable heterogeneity. To further explore how the effect of tick sizes depends on initial stock liquidity, I split the sample of non-OBX stocks into equally-sized terciles based on stock trading volume. For each stock in the non-OBX sample, I compute the average trading volume in January 2008 (the first month in the sample period). Stocks are then sorted into terciles based on the January 2008 trading volume. The tercile a stock belongs to remains the same throughout the sample period 2008 – 2011. Moreover, in the upcoming empirical analyses I only use data from February 2008 and onwards. This procedure ensures that the tercile formation itself cannot be affected by tick size changes.

Table 5 presents descriptive statistics which illustrate the variation in stock characteristics that the trading volume terciles capture. First, although the terciles are formed based on a single liquidity metric — stock trading volume — Table 5 shows that the tercile formation could equally well have been based on any other market quality metric. Specifically, the table shows that Tercile 1 (least traded) consistently has the widest spreads, most shallow books, highest volatility, and (naturally) the lowest trading volumes. For example, the median trading volume in Tercile 1 is 80000NOK (1 USD $\approx$ 8 NOK), the median order book depth is 75 000NOK, and the median relative quoted spread is almost 5% of the current midquote. Tercile 3 (most traded), in contrast, represents a reasonably liquid trading environment, with a median trading volume of almost two million NOK, a median order book depth of 162 000NOK, and a median relative quoted spread of 1.3% of the current midquote. Indeed, along some dimensions of stock liquidity, such as order book depth and transaction costs, trading in Tercile 3 stocks appears comparable to the statistics of the liquid large-cap stocks in Table 2.

Second, the trading volume terciles capture variation in how constrained the bid-ask spread is by the tick size — a variation that is potentially important for understanding the empirical results. O'Hara et al. (2015) explore whether changes to the relative tick size affect stocks in a one-tick environment (the bid-ask spread is equal to the tick size) and stocks in multi-tick environments differently. They show that in the one-tick environment, an increase in the relative tick size leads to more trading volume and more order book depth. In contrast, in the multi-tick environment an increase in the relative tick size leads to lower trading volume and less order book depth. Table 5 shows that stocks in Tercile 3 tend to trade close to a one-tick environment, with a median ticks-per-spread of only 3. In contrast, Terciles 2 and 3 tend to trade in a multi-tick environment, with median ticks-per-spread of 6 and 10 respectively.

Finally, the trading volume terciles capture a variation in market capitalization. The average market capitalization is monotonically increasing in the terciles, from 740 million NOK in Tercile 1 to 1505 million NOK in Tercile 2 and finally 2716 million NOK in Tercile 3. For comparison, the eligibility criteria for the recently implemented Tick Size Pilot Program in the United States is that stocks should have a market capitalization of less than \$3 (approximately 18 billion NOK). Clearly, judged by this criteria alone, the average stock in all the trading volume terciles would be eligibile for the tick size pilot.

Table 7 presents estimates from the regression discontinuity design applied separately to each of the trading volume terciles. For the most illiquid stocks (Tercile 1), there are no measurable effects of increasing the tick size on the quality of trading. Specifically, increasing the tick size for this sample of stocks does not affect spread measures of liquidity, order book depth, or trading volume. In contrast, for Tercile 3 (most traded), increasing the tick size causes significantly wider spreads and deeper order books, suggesting that the average effect for non-OBX stocks in Table 6 is primarily driven by the most liquid stocks in the distribution.

Splitting the sample into terciles provides a somewhat coarse insight into how the effect of tick sizes differs depending on initial stock liquidity. As an alternative approach to illustrate treatment effect heterogeneity, I split the sample into quantiles instead terciles, using the same ranking procedure as before. Table 8 presents estimates of the regression discontinuity design applied separately to each of the quantiles. The table confirms the impression from Table 7. For the bottom 60% of the liquidity distribution, I find no effects of increasing the tick size on either liquidity or trading volume. Instead, for the top 40% of the liquidity distribution there is a strong and statistically significant impact of tick size changes on both spreads and order book depths, but no impact on volatility or trading volume.

6 Discussion and concluding remarks

Estimates from a so-called regression discontinuity design reveal that the causal effect of increasing the tick size, the minimum price increment on a stock exchange, differs depending on the initial stock liquidity. For liquid stocks at the Oslo Stock Exchange in the period $2008 - 2011$, increasing the tick size leads to wider bid-ask spreads and deeper order books, and has a weakly significant and potentially time-varying positive impact on trading volume. For the most illiquid stocks at the Oslo Stock Exchange, however, changing the tick size has no impact on bid-ask spreads, order book depths, volatility, or trading volume.

There are several implications of the results in this paper. First, my empirical results have implications for the current theoretical debate over the potentially heterogeneous impact of tick sizes on stocks with different liquidity. Buti et al. (2015) predict that increasing the tick size for illiquid stock may improve stock liquidity and decrease trading volume. My results provide little empirical support for this prediction. Meanwhile, my results suggest that increasing the tick size for liquid stocks may in fact increase both order book depth and widen the bid-ask spread, while at the same time increasing trading volume. These results are largely consistent with the theoretical predictions by Buti et al. (2015) for liquid order books.

Second, the recently implemented "Tick Size Pilot Program" in the United States, which has increased the tick size for a large number of small and medium sized firms, reflects a similar suspicion that the "one size fits all" penny tick size in the United States may not be optimal for the entire distribution of firms. The main argument behind the tick size pilot is that small tick sizes may be optimal for liquid (large-cap) securities, as it will reduce trading costs, while large tick sizes may be optimal for illiquid (small-cap) securities, as it will provide incentives for liquidity provision in these stocks and therefore enhance overall trading volume. The results in this paper suggest that smaller tick sizes may reduce transaction costs for liquid stocks, however only at the expense of reduced order book depth. For illiquid stocks, however, such a trade-off does not exist as the tick size does not appear to affect any measure of small-cap market quality. Thus, my estimates suggest that other market structure tools than tick sizes are needed if the object is to improve the quality of trading in illiquid stocks.

Third, the results in this paper illustrate the importance of evaluating heterogeneous responses to equity market policy changes. I show that tick size changes appear to have heterogeneous effects across the stock liquidity distribution — a large portion of the liquidity distribution experiences no effect from tick size changes (illiquid stocks) while a small portion of the liquidity distribution experiences a considerable effect from tick size changes (liquid stocks). Nevertheless, the resulting average treatment effect, which is estimated across the entire distribution of stocks, is measured to be highly statistically significant. In terms of policy advice and extrapolation to alternative contexts, this average treatment effect may be seriously misleading when not accompanied with information about the underlying effect heterogeneity.

Meanwhile, I also caution about the interpretation of the results in the present paper. Illiquid stocks are, in my setting, defined jointly by their low trading volume, shallow order books, high transaction costs, and their unconstrained bid-ask spreads. This joint definition of illiquidity is not by purposeful design, but is rather an artifact of significant correlation between liquidity measures — differentiating stocks on one liquidity measure typically implies differentiating on another liquidity measure as well. For this reason, I cannot determine whether heterogeneity in the effect of tick sizes is driven primarily by any specific liquidity measure, or simply by the combination of all the liquidity measures. In their theoretical model, Buti et al. (2015) define illiquid stocks exclusively based on order book depth. My empirical analysis cannot, therefore, be interpreted as a direct test of the theoretical predictions in Buti et al. (2015). Instead, my empirical results can be interpreted as showing that the effect of tick sizes varies depending on a more general definition of stock liquidity.

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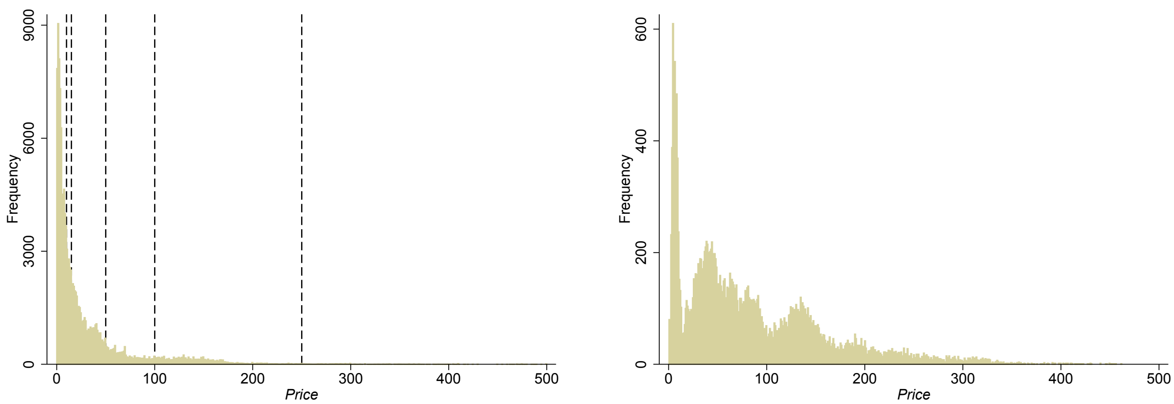
7 Figures

Figure 1: Stock price density

(a) Non-OBX

(b) OBX

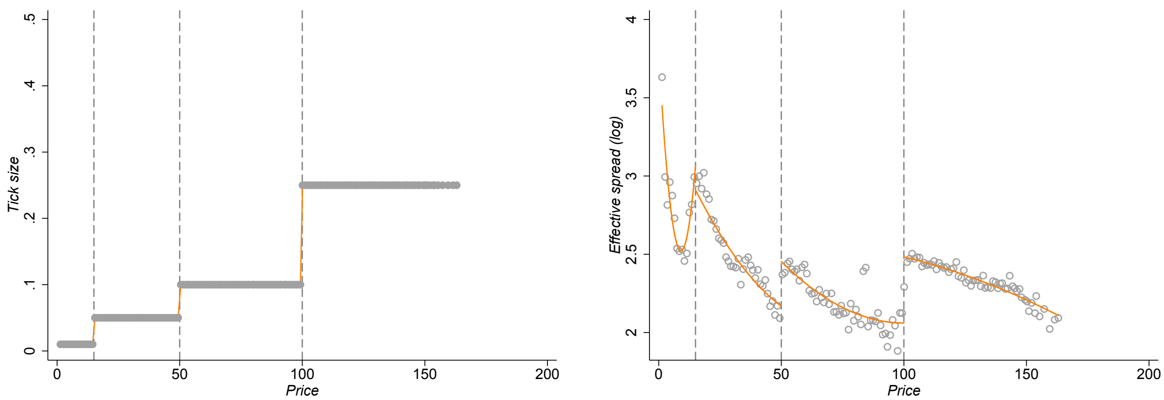


Note: The figure presents a histogram of stock prices in the period $2008 - 2011$, separately for non-OBX index stocks (panel a) and OBX index stocks (panel b). Each bar has a width of 1NOK, and there are 500 bars. Vertical breaks indicate price levels where the tick size increases. Vertical breaks have been excluded from panel (b) because the tick size schedule for OBX index stocks changed during the time period $2008 - 2011$.

Figure 2: Illustration of regression discontinuity design

(a) Tick size over price

(b) Log(Effective spread) over price



Note: The figure illustrates the regression discontinuity design. Panel (a) plots tick sizes as a function of prices. Panel (b) plots effective spreads (log) as a function of prices. Both panels (a) and (b) plot observations from a sample of OBX index stocks in the period January 2008 – May 2009. Vertical dashed lines indicate stock price levels where the tick size increases. The regression discontinuity design estimates the impact of tick sizes as the discontinuous change in outcomes at the exact price levels where the tick size changes.

8 Tables

Table 1: Tick size schedules

OBX index stocks					
June, 2003 - August, 2006		*Sept. 2006 - May, 2009*		*Sept. 2009 - Dec. 2012*	
Price band	**Tick size**	**Price band**	**Tick size**	**Price band**	**Tick size**
0 - 9.99	0.01	0 - 14.99	0.01	0 - 0.4999	0.0001
10 - 49.9	0.10	15 - 49.95	0.05	0.5 - 0.9995	0.0005
50 - 149.75	0.25	50 - 99.9	0.1	1 - 4.9990	0.001
150 - 999.5	0.50	100 - 249.75	0.25	5 - 9.995	0.005
1000 -	1.00	250 - 499.50	0.5	10 - 49.990	0.01
		>500	1	50 - 99.95	0.05
				100 - 499.90	0.1
				500 - 999.50	0.5
				1000 - 4999	1
				5000 - 9995	5
				>10000	10
Non-OBX index stocks					
June, 2003 - August, 2006		*Sept. 2006 - May, 2009*		*Sept. 2009 - Dec. 2012*	
Price band	**Tick size**	**Price band**	**Tick size**	**Price band**	**Tick size**
0 - 9.99	0.01	0 - 9.99	0.01	0 - 9.99	0.01
10 - 49.9	0.10	10 - 14.95	0.05	10 - 14.95	0.05
50 - 149.75	0.25	15 - 49.9	0.1	15 - 49.9	0.1
150 - 999.50	0.50	50 - 99.75	0.25	50 - 99.75	0.25
1000 -	1.00	100 - 249.5	0.5	100 - 249.5	0.5
		>250	1	>250	1

Note: The table shows the evolution of tick size schedules at OSE. Tick sizes are determined by stock price bands (in NOK). The top panel shows tick size schedules for large-cap stocks. The bottom panel shows tick size schedules for small-cap stocks.

Table 2: Summary statistics

	μ	σ	Min.	Median	Max.	N
OBX stocks						
Market cap. (mNOK)	29200.59	38028.17	0.00	13426.00	217595.56	16555
Relative spread (bps)	29.47	20.54	4.09	24.45	461.52	16554
Realized spread (bps)	2.21	6.98	-53.08	1.46	640.16	16548
Depth (thousands NOK)	737.77	1451.47	18.08	433.75	45649.04	16554
Realized volatility (pp)	0.74	1.53	0.02	0.45	46.86	16542
Volume (mNOK)	155.71	223.88	0.01	97.73	13443.04	16555
Stock price	51.56	38.07	0.38	45.04	165.00	16555
Tick size	0.05	0.06	0.00	0.05	0.25	16555
Relative tick size	0.10	0.09	0.02	0.08	1.03	16555
Ticks-per-spread	3.69	5.59	0.00	2.00	207.50	16553
non-OBX stocks						
Market cap. (mNOK)	1799.81	3080.58	0.00	857.24	105517.95	124770
Relative spread (bps)	369.42	295.47	11.49	286.71	1497.12	136800
Realized spread (bps)	59.74	137.24	-1740.74	26.68	2352.94	93227
Depth (thousands NOK)	348.30	4425.28	0.06	105.72	481635.51	145325
Realized volatility (pp)	1.03	1.52	0.02	0.70	49.30	75209
Volume (mNOK)	4.77	65.80	0.00	0.43	17368.01	124759
Stock price	23.87	30.90	0.02	12.00	198.50	124770
Tick size	0.08	0.11	0.01	0.05	0.50	124770
Relative tick size	0.57	1.76	0.10	0.36	50.00	124770
Ticks-per-spread	10.44	18.13	0.00	5.00	1600.00	123924

Note: The table gives summary statistics for OBX index stocks (large-caps) and non-OBX index stocks (small-caps) at the Oslo Stock Exchange (OSE) in the period $2008 - 2011$. The stock characteristics are market capitalization (millions NOK); relative and realized spreads (basis points); order book depth (thousands NOK); realized volatility (millions NOK); stock price (NOK); tick size (NOK); relative tick size (tick size relative to stock price); ticks-per-spread (tick size relative to quoted spread). The table lists means (μ), standard deviations (σ), minimum (Min.) and maximum values (Max.), medians, and number of observations (N).

Table 3: Before-and-after estimates of tick size reduction

	Dependent variable				
	Relspread	*Rspread*	*Depth*	*Volatility*	*Volume*
β	-0.10*	-0.07	-0.42***	0.00	-0.12*
	(-2.27)	(-0.53)	(-9.36)	(0.82)	(-2.14)
N	500	332	500	500	500
Adj. R^2	0.01	-0.00	0.07	-0.00	0.00

Note: The table gives before-and-after estimates of the impact of the July 6, 2009 tick size reduction for OBX index stocks at the Oslo Stock Exchange. The regression specification is $y_{it} = \alpha + \beta Post_t + \epsilon_{it}$, where $Post_t = 1$ for observations after July 6, 2009. The sample comprises ten trading days before and ten trading days after July 6, 2009 for all the 25 stocks in the OBX index. *Relspread* is the relative bid-ask spread, log-transformed. *Rspread* is the realized spread, log-transformed. *Depth* is the order book depth, log-transformed. *Volatility* is realized volatility measured in percentages. *Volume* is the NOK trading volume, log-transformed. Standard errors clustered at the stock-level. t-statistics in parentheses.
* $p < 0.05$, ** $p < 0.025$, *** $p < 0.01$

Table 4: Tick size price threshold crossings

	Non-OBX sample in 2008-2011 Number of price threshold crossings
NOK10 from below	408
NOK15 from below	387
NOK50 from below	236
NOK100 from below	92
NOK10 from above	437
NOK15 from above	428
NOK50 from above	247
NOK100 from above	95
Unique stocks crossing any threshold	157
	OBX sample in 2008-2011 Number of price threshold crossings
NOK10 from below	28
NOK15 from below	13
NOK50 from below	68
NOK100 from below	54
NOK10 from above	34
NOK15 from above	17
NOK50 from above	74
NOK100 from above	57
Unique stocks crossing any threshold	26

Note: The table summarizes the occurrence of tick size price threshold crossings in the sample period 2008–2011 for non-OBX index stocks. Threshold crossings are summarized separately for crossings from below and above a price threshold. Threshold crossings are defined at the daily level using end-of-day prices.

Table 5: Summary statistics: Liquidity terciles

	μ	σ	Min.	Median	Max.	N
Tercile 1 (Least traded)						
Market cap. (mNOK)	740.67	827.30	2.10	498.37	6075.00	27069
Relative spread (bps)	556.27	321.79	26.49	483.03	1497.12	34092
Realized spread (bps)	85.22	158.30	-1740.74	48.10	1698.83	13236
Depth (thousands NOK)	151.24	772.95	0.59	75.61	40552.00	38950
Realized volatility (pp)	1.19	1.40	0.02	0.83	36.02	7868
Volume (mNOK)	1.14	15.05	0.00	0.08	1333.67	27009
Stock price	17.18	18.46	0.08	10.85	129.00	27069
Tick size	1.20	1.31	0.20	1.00	10.00	27069
Relative tick size	0.51	0.70	0.10	0.38	12.50	27069
Ticks-per-spread	16.68	22.57	0.40	10.00	700.00	26695
Tercile 2						
Market cap. (mNOK)	1505.67	2426.09	0.95	642.97	65955.11	40655
Relative spread (bps)	384.22	259.14	12.07	323.17	1497.12	44120
Realized spread (bps)	76.25	159.88	-1172.24	39.05	2248.06	29326
Depth (thousands NOK)	213.27	744.75	1.85	95.13	35173.72	45449
Realized volatility (pp)	1.11	1.44	0.02	0.75	35.56	21100
Volume (mNOK)	2.41	18.07	0.00	0.25	1338.78	40814
Stock price	27.15	36.44	0.02	12.30	198.50	40655
Tick size	1.98	2.70	0.20	1.00	10.00	40655
Relative tick size	0.61	1.65	0.10	0.37	50.00	40655
Ticks-per-spread	10.62	15.22	0.20	6.00	400.00	40478
Tercile 3 (Most traded)						
Market cap. (mNOK)	2716.11	4094.54	6.64	1798.84	105517.95	46955
Relative spread (bps)	205.87	190.54	11.49	137.13	1482.50	47309
Realized spread (bps)	41.97	111.66	-847.46	19.01	1666.67	44332
Depth (thousands NOK)	632.43	7553.39	4.50	162.43	481635.50	47809
Realized volatility (pp)	0.98	1.62	0.02	0.66	49.30	41335
Volume (mNOK)	9.11	55.58	0.00	2.03	6034.40	46858
Stock price	25.04	32.65	0.02	11.00	198.50	46955
Tick size	1.75	2.39	0.00	1.00	10.00	46955
Relative tick size	0.63	2.36	0.02	0.35	50.00	46955
Ticks-per-spread	6.03	12.11	0.00	3.00	1070.00	46882

Note: The table gives summary statistics from the time period $2008-2011$ separately for terciles that are formed based on average trading volume in January 2008. The stock characteristics are market capitalization (millions NOK); relative and realized spreads (basis points); order book depth (thousands NOK); realized volatility (millions NOK); stock price (NOK); tick size (NOK); relative tick size (tick size relative to stock price); ticks-per-spread (tick size relative to quoted spread). The table lists means (μ), standard deviations (σ), minimum (Min.) and maximum values (Max.), medians, and number of observations (N).

Table 6: Main results

	Relspread	Rspread	Depth	Volatility	Volume
	OBX sample in period: 2008 - May 2009				
	Relspread	*Rspread*	*Depth*	*Volatility*	*Volume*
τ	0.20***	0.39***	0.20***	0.16*	-0.01
	(7.43)	(5.18)	(3.42)	(2.29)	(-0.16)
N	6530	4986	6530	6518	6530
Adj. R^2	0.81	0.21	0.82	0.12	0.71
	OBX sample in period: September 2009 - 2011				
	Relspread	*Rspread*	*Depth*	*Volatility*	*Volume*
τ	0.12	0.58***	0.73***	0.10*	0.22**
	(1.08)	(3.80)	(5.55)	(2.29)	(2.67)
N	10023	7411	10023	10024	10025
Adj. R^2	0.87	0.33	0.90	0.11	0.82
	non-OBX sample in period: 2008 - 2011				
	Relspread	*Rspread*	*Depth*	*Volatility*	*Volume*
τ	0.07***	0.13***	0.10***	0.04*	0.01
	(4.54)	(6.11)	(4.16)	(2.17)	(0.17)
N	121296	82093	123954	74997	124770
Adj. R^2	0.66	0.37	0.51	0.17	0.51

Note: The table gives regression discontinuity estimates of the effect of increasing the tick size on market quality outcomes, for stocks at the Oslo Stock Exchange in the period 2008 – 2011. The regression discontinuity design is run separately for OBX index stocks and non-OBX index stocks. The regression specification is $y_{it} = \alpha_i + \alpha_t + \tau Ticksize_{it} + f(price_{it}) + \varepsilon_{it}$, where $f(price_{it})$ is a 7th order polynomial of the stock price and α_i and α_t are stock and time fixed effects, respectively. The coefficient τ identifies discrete jumps in y_{it} at the exact stock price levels where the tick size changes. *Relspread* is the relative bid-ask spread, log-transformed. *Rspread* is the realized spread, log-transformed. *Depth* is the order book depth, log-transformed. *Volatility* is realized volatility measured in percentages. *Volume* is the NOK trading volume, log-transformed. The τ regression coefficient has been scaled, and can be interpreted as the change in y_{it} given a 0.05NOK increase in the tick size. Standard errors clustered at the stock-level. t-statistics in parentheses.

* $p < 0.05$, ** $p < 0.025$, *** $p < 0.01$

Table 7: Tercile regressions

	Tercile regressions: 2008-2011				
	Relspread	*Rspread*	*Depth*	*Volatility*	*Volume*
Tercile 1 (Least traded)					
τ	0.05	-0.02	0.06	0.10	0.06
	(1.86)	(-0.45)	(1.35)	(1.59)	(0.66)
N	24762	10856	25905	7737	26344
Adj. R^2	0.42	0.26	0.38	0.24	0.26
Tercile 2					
τ	0.05	0.07	0.01	-0.01	-0.06
	(1.80)	(1.97)	(0.42)	(-0.25)	(-0.93)
N	38657	24602	39364	20206	39484
Adj. R^2	0.55	0.29	0.42	0.25	0.33
Tercile 3 (Most traded)					
τ	0.09***	0.18***	0.17***	0.06*	0.05
	(4.57)	(5.40)	(3.90)	(2.13)	(1.42)
N	43742	37552	44080	38495	44101
Adj. R^2	0.61	0.32	0.53	0.15	0.47

Note: The table gives regression discontinuity estimates of the effect of increasing the tick size on market quality outcomes, for stocks at the Oslo Stock Exchange in the period February 2008 to December 2011. The regression discontinuity design is run separately for terciles that are formed based on average trading volume in January 2008. The regression specification is $y_{it} = \alpha_i + \alpha_t + \tau Ticksize_{it} + f\left(price_{it}\right) + \varepsilon_{it}$, where $f\left(price_{it}\right)$ is a 7th order polynomial of the stock price and α_i and α_t are stock and time fixed effects, respectively. The coefficient τ identifies discrete jumps in y_{it} at the exact stock price levels where the tick size changes. *Relspread* is the relative bid-ask spread, log-transformed. *Rspread* is the realized spread, log-transformed. *Depth* is the order book depth, log-transformed. *Volatility* is realized volatility measured in percentages. *Volume* is the NOK trading volume, log-transformed. The τ regression coefficient has been scaled, and can be interpreted as the change in y_{it} given a 0.05NOK increase in the tick size. Standard errors clustered at the stock-level. t-statistics in parentheses.
** $p < 0.05$, ** $p < 0.025$, *** $p < 0.01$*

Table 8: Quantile regressions

	Quantile regressions: 2008-2011				
	Relspread	*Rspread*	*Depth*	*Volatility*	*Volume*
Quantile 1 (Least traded)					
τ	0.04	-0.06	0.03	0.26**	-0.05
	(1.56)	(-0.70)	(0.45)	(2.46)	(-0.41)
N	11978	4674	12854	3006	13244
Adj. R^2	0.42	0.26	0.41	0.26	0.23
Quantile 2					
τ	-0.02	-0.05	0.07	0.02	0.15
	(-0.43)	(-1.05)	(1.67)	(0.36)	(1.62)
N	20839	10905	21375	8299	21439
Adj. R^2	0.44	0.26	0.35	0.24	0.26
Quantile 3					
τ	0.04	0.03	-0.00	-0.06	-0.05
	(1.22)	(0.50)	(-0.05)	(-0.73)	(-0.63)
N	24152	14962	24462	12143	24556
Adj. R^2	0.52	0.25	0.43	0.22	0.30
Quantile 4					
τ	0.09***	0.12***	0.14***	0.05	0.05
	(3.17)	(3.47)	(3.02)	(1.64)	(0.65)
N	25528	20170	25781	19300	25808
Adj. R^2	0.58	0.27	0.46	0.21	0.38
Quantile 5 (Most traded)					
τ	0.08***	0.18***	0.16***	0.04	0.05
	(3.00)	(4.73)	(2.96)	(1.39)	(1.54)
N	24664	22258	24877	23577	24882
Adj. R^2	0.60	0.36	0.53	0.15	0.48

Note: The table gives regression discontinuity estimates of the effect of increasing the tick size on market quality outcomes, for stocks at the Oslo Stock Exchange in the period February 2008 to December 2011. The regression discontinuity design is run separately for quantiles that are formed based on average trading volume in January 2008. The regression specification is $y_{it} = \alpha_i + \alpha_t + \tau Ticksize_{it} + f\left(price_{it}\right) + \varepsilon_{it}$, where $f\left(price_{it}\right)$ is a 7th order polynomial of the stock price and α_i and α_t are stock and time fixed effects, respectively. The coefficient τ identifies discrete jumps in y_{it} at the exact stock price levels where the tick size changes. *Relspread* is the relative bid-ask spread, log-transformed. *Rspread* is the realized spread, log-transformed. *Depth* is the order book depth, log-transformed. *Volatility* is realized volatility measured in percentages. *Volume* is the NOK trading volume, log-transformed. The τ regression coefficient has been scaled, and can be interpreted as the change in y_{it} given a 0.05NOK increase in the tick size. Standard errors clustered at the stock-level. t-statistics in parentheses.

* $p < 0.05$, ** $p < 0.025$, *** $p < 0.01$

A Robustness of regression discontinuity design

This section explores the sensitivity of the regression discontinuity design to alternative specifications. As described in Section 4, I implement the RD design with the following regression specification:

$$y_{it} = \alpha_i + \alpha_t + \tau Ticksize_{it} + f\left(Price_{it}\right) + \varepsilon_{it} \tag{5}$$

where y_{it} is some outcome for stock i on date t; $Ticksize_{it}$ is the discrete tick size; and $f\left(Price_{it}\right)$ is a flexible function of the stock price. If specified correctly, $f\left(Price_{it}\right)$ captures all dependence of y_{it} and $Ticksize_{it}$ on the stock price away from the tick size price thresholds, such that the coefficient τ is estimated using only the variation in the tick size that occurs at the exact stock price levels where the tick size changes. The coefficient τ can be interpreted as the causal effect of tick sizes on y_{it}, under the identifying assumption that stocks are comparable in both their observable and unobservable stock characteristics at the price thresholds.

This section modifies equation 5 threefold. First, Section A.1 allows for a variety of different polynomial specifications of $f\left(Price_{it}\right)$. Second, Section A.2 tests for discontinuities in y_{it} at placebo tick size price thresholds. Third, Section A.3 adds control variables to equation 5. All the robustness tests are based on the sample of non-OBX index stocks in the period $2008 - 2011$. Therefore, the results in this section can be compared to the baseline results presented in the bottom panel of Table 6.

A.1 Alternative polynomial specifications

The regression discontinuity specification in Section 5 assumes that the relationship between stock prices and outcomes can be adequately captured by a seventh order polynomial. In Table 9, however, I relax this assumption and explore the robustness of the RD design to alternative polynomial specifications. The table estimates equation 5 separately for linear, quadratic, cubic, quartic, and quintic specifications of $f\left(\right)$. Table 9 shows that the estimates of τ remain fairly stable across polynomial specifications.

Table 9: Alternative polynomial specifications

	Polynomial specification				
	Linear	Quadratic	Cubic	Quartic	Quintic
Relative spread	0.04***	0.06***	0.05***	0.06***	0.07***
	(3.12)	(4.44)	(3.90)	(4.54)	(4.92)
N	121296	121296	121296	121296	121296
Adj. R^2	0.65	0.65	0.65	0.65	0.65
Realized spread	0.10***	0.11***	0.10***	0.13***	0.15***
	(5.19)	(6.83)	(5.64)	(6.46)	(7.01)
N	82093	82093	82093	82093	82093
Adj. R^2	0.36	0.36	0.36	0.37	0.37
Depth	0.11***	0.08***	0.11***	0.10***	0.10***
	(4.19)	(3.09)	(4.13)	(4.17)	(4.09)
N	123954	123954	123954	123954	123954
Adj. R^2	0.49	0.51	0.51	0.51	0.51
Volatility	0.02	0.04***	0.02	0.04**	0.06***
	(1.46)	(2.74)	(1.40)	(2.44)	(2.88)
N	74997	74997	74997	74997	74997
Adj. R^2	0.16	0.17	0.17	0.17	0.17
Trading volume	0.02	0.00	0.01	0.01	0.00
	(0.64)	(0.03)	(0.38)	(0.33)	(0.05)
N	124770	124770	124770	124770	124770
Adj. R^2	0.51	0.51	0.51	0.51	0.51

Note: The table gives regression discontinuity estimates of the effect of increasing the tick size on market quality outcomes, for non-OBX index stocks at the Oslo Stock Exchange in the period $2008-2011$. The regression specification is $y_{it} = \alpha_i + \alpha_t + \tau Ticksize_{it} + f\left(price_{it}\right) + \varepsilon_{it}$, where $f\left(price_{it}\right)$ represents a flexible polynomial of the stock price and α_i and α_t are stock and time fixed effects, respectively. The regression specification is estimated separately for linear through cubic polynomial specifications of $f\left(price_{it}\right)$. The coefficient τ identifies discrete jumps in y_{it} at the exact stock price levels where the tick size changes. *Relspread* is the relative bid-ask spread, log-transformed. *Rspread* is the realized spread, log-transformed. *Depth* is the order book depth, log-transformed. *Volatility* is realized volatility measured in percentages. *Volume* is the NOK trading volume, log-transformed. The top panel includes the natural logarithm of market capitalization as a control variable. The bottom panel includes both market capitalization and $y_{i,t-1}$ as control variables. The τ regression coefficient has been scaled, and can be interpreted as the change in y_{it} given a 0.05NOK increase in the tick size. Standard errors clustered at the stock-level. t-statistics in parentheses. ** $p < 0.05$, ** $p < 0.025$, *** $p < 0.01$*

A.2 Placebo thresholds

The identifying assumption in the regression discontinuity design is that the stock price thresholds that increase or decrease the tick size only affect stock outcomes through their impact on the tick size. To assess whether or not this assumption is plausible, I explore whether the effects documented in Section 5 are exclusive to stock price thresholds that mandate tick size changes. To this end, I generate a 'placebo' tick size variable which starts at 0.01NOK and increases to 0.1NOK, 0.2NOK, 0.3NOK, and 0.4NOK at the 25NOK, 50NOK, 75NOK, and 125NOK price thresholds, respectively.

In Table 10, I estimate the regression discontinuity design with both the actual tick size variable ($Ticksize_{it}$) and the 'placebo' tick size variable ($Ticksize_{it}^{Placebo}$) as explanatory variables. Table 10 shows that the estimated impact of $Ticksize_{it}$ remains similar to estimates from the baseline specification. Reassuringly, the table also shows that for all outcome variables except for realized volatility, there is no impact of $Ticksize_{it}^{Placebo}$.

Table 10: Placebo tests

	Dependent variable				
	Relspread	*Rspread*	*Depth*	*Volatility*	*Volume*
τ	0.06***	0.13***	0.09***	0.02	-0.00
	(4.66)	(5.88)	(3.87)	(1.62)	(-0.04)
$\tau^{Placebo}$	-0.01	-0.02	-0.05	-0.07*	-0.03
	(-0.34)	(-0.61)	(-1.48)	(-2.25)	(-0.52)
N	121296	82093	123954	74997	124770
Adj. R^2	0.66	0.37	0.51	0.17	0.51

Note: The table gives regression discontinuity estimates of the effect of increasing the tick size on market quality outcomes, for non-OBX index stocks at the Oslo Stock Exchange in the period $2008-2011$. The regression specification is $y_{it} = \alpha_i + \alpha_t + \tau Ticksize_{it} + \tau^{Placebo} Ticksize_{it}^{Placebo} + f\left(price_{it}\right) + \varepsilon_{it}$, where $f\left(price_{it}\right)$ is a 7th order polynomial of the stock price and α_i and α_t are stock and time fixed effects, respectively. $Ticksize_{it}$ is the tick size based on the actual tick size schedule and $Ticksize_{it}^{Placebo}$ is the tick size based on a fictional tick size schedule with tick size price thresholds at 25NOK, 75NOK, and 125NOK. *Relspread* is the relative bid-ask spread, log-transformed. *Rspread* is the realized spread, log-transformed. *Depth* is the order book depth, log-transformed. *Volatility* is realized volatility measured in percentages. *Volume* is the NOK trading volume, log-transformed. The τ and $\tau^{Placebo}$ regression coefficients have been scaled, and can be interpreted as the change in y_{it} given a 0.05NOK increase in the tick size. Standard errors clustered at the stock-level. t-statistics in parentheses.
** $p < 0.05$, ** $p < 0.025$, *** $p < 0.01$*

A.3 Control variables

If the regression discontinuity design is valid, there is no need to add control variables to equation 5 (Lee and Lemieux 2010). This is because randomness in whether a stock is priced marginally above or marginally below a tick size price threshold ensures that stocks on either side of the price threshold are comparable in their observable characteristics. Nevertheless, a common validity test in the regression discontinuity design literature is to estimate the RD design with non-outcome covariates as controls.

In my setting, there are few candidate control variables — most of the covariates can either be considered as outcomes (such as the liquidity measures) or the covariates do not vary on a sufficiently high frequency (such as earnings or assets). Nevertheless, there are two non-outcome daily frequency covariates that can be added to equation 5. The first is the natural logarithm of daily market capitalization. The second is the lagged outcome variable ($y_{i,t-1}$). As discussed in Lee and Lemieux (2010), adding the $y_{i,t-1}$ as a control may improve statistical precision when y_{it} is highly persistent.

In the top panel of Table 11, I estimate the regression discontinuity design using only market capitalization as a control variable. The estimates of τ from this specification are almost identical to the baseline specification. In the bottom panel of Table 11, I control for both market capitalization and $y_{i,t-1}$. Including $y_{i,t-1}$ in equation 5 reduces the magnitudes of the regression coefficients, but the statistical inference remains unchanged.

Table 11: Control variables

	Controlling for market cap.				
	Relspread	*Rspread*	*Depth*	*Volatility*	*Volume*
τ	0.06***	0.12***	0.11***	0.04**	0.03
	(4.49)	(6.28)	(4.59)	(2.56)	(1.02)
N	119223	80763	121744	73826	122471
Adj. R^2	0.69	0.39	0.54	0.18	0.53
	Controlling for market cap. and lagged outcome				
	Relspread	*Rspread*	*Depth*	*Volatility*	*Volume*
τ	0.02***	0.10***	0.04***	0.03**	0.03
	(4.88)	(6.02)	(5.07)	(2.28)	(1.23)
N	91792	50297	94843	49637	95297
Adj. R^2	0.83	0.43	0.77	0.29	0.56

Note: The table gives regression discontinuity estimates of the effect of increasing the tick size on market quality outcomes, for non-OBX index stocks at the Oslo Stock Exchange in the period $2008 - 2011$. The regression specification is $y_{it} = \alpha_i + \alpha_t + \tau Ticksize_{it} + f\left(price_{it}\right) + \varepsilon_{it}$, where $f\left(price_{it}\right)$ is a 7th order polynomial of the stock price and α_i and α_t are stock and time fixed effects, respectively. The coefficient τ identifies discrete jumps in y_{it} at the exact stock price levels where the tick size changes. *Relspread* is the relative bid-ask spread, log-transformed. *Rspread* is the realized spread, log-transformed. *Depth* is the order book depth, log-transformed. *Volatility* is realized volatility measured in percentages. *Volume* is the NOK trading volume, log-transformed. The top panel includes the natural logarithm of market capitalization as a control variable. The bottom panel includes both market capitalization and $y_{i,t-1}$ as control variables. The τ regression coefficient has been scaled, and can be interpreted as the change in y_{it} given a 0.05NOK increase in the tick size. Standard errors clustered at the stock-level. t-statistics in parentheses.

** $p < 0.05$, ** $p < 0.025$, *** $p < 0.01$*

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