Zero Tick: The impact of trading behavior on market quality with near continuous tick size.

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Abstract

We analyze a cryptocurrency market structure setting where trading resembles equity markets, but spreads are unconstrained, assets have limited fundamental value and tick sizes are extremely small, facilitating undercutting. Using a high frequency dataset, we find that a significant tick size increase in this market reduces undercutting, encouraging traders to post more and larger limit orders and market orders. Increased liquidity provision also lowers quoted, effective and realized spreads for both institutional and retail sized trades and decreases short-term volatility. These results demonstrate that increasing extremely small tick sizes for unconstrained spreads leads to enhanced market quality. Our findings thus confirm theoretical predictions of a convex shape relationship between tick size and spread and verify that optimal tick size is non-zero. We contribute to the optimal tick size debate surrounding the US pilot study and provide evidence in support of a dynamic tick size, where the minimum tick size is linked to the share price and liquidity of the stock.

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1 Introduction

High overall market quality is critical for trading venues to attract traders in increasingly fragmented markets, with almost thirty percent of all US equity volume executed in off-exchange venues (O'Hara and Ye, 2011). While there is no single metric to measure market quality, the minimum tick size is one aspect of market quality that is controlled by an exchange. The optimality of the minimum tick size has attracted a lot of attention recently with the US conclusion of the pilot study, which investigated the merits of raising the minimum tick size for small-cap stocks to incentivize market participants to provide liquidity (Bartlett and McCrary, 2017; Chung, Lee and Rosch, 2018; Griffith and Roseman, 2018; Rindi and Werner, 2017).

Theoretical models show that optimal tick size must be small to minimize the indirect trading costs associated with bid-ask spread, but it must be non-zero to enforce time and price priority, incentivizing investors to provide liquidity with limit orders (Harris, 1991; Cordella and Foucault, 1999; Foucault, Kadan, and Kandel, 2005). A non-zero tick size also simplifies the trader's information set, reducing the costs of negotiation and the potential for costly errors (Harris, 1991). When the minimum tick size approaches zero, trading costs are high as traders can price improve limit orders by an economically insignificant amount, undercutting larger orders. This undercutting behavior disincentivizes traders from exposing large orders, encouraging traders to cross the spread to get executed. Widening the pricing increment forces traders to undercut by a larger amount, increasing its cost and reducing its attractiveness. The reduced threat of undercutting from more discrete tick sizes enforces price-time priority and encourages liquidity provision, leading to a lower overall cost of trading. While the minimum spread creates a cost for liquidity demanders counteracting some of the gains of liquidity provision, if spreads remain unconstrained, traders will switch from market orders to limit orders due to the reduced probability of undercutting. This increases depth and decreases volume, leading to an overall increase in market quality. However, once tick sizes are large enough to become binding, the execution probability of limit orders decreases due to longer queues and encourages traders to switch from limit orders back to market orders. This increases spreads, decreases depth, increases volume and causes an overall deterioration in market quality. The optimal tick size thus represents a trade-off between the benefits of a non-zero tick and the costs that a tick imposes. This predicted convex shape relationship between trading cost and tick size depends on many factors including the average trade size, trader type and liquidity of the book (Angel, 1997; Foucault et al., 2005; Seppi, 1997; Werner et al., 2015).

We extend the previous research on the impact of tick size increases on market quality and trading behavior by examining high frequency trade and quote data from a cryptocurrency exchange Kraken, where tick sizes are typically very small compared to the equity market and the relative tick size is close to zero. We use two tick size increases in August and September 2017 as natural experiments to analyze the relation between the tick size and liquidity provision, spreads and volatility for six currency pairs between Bitcoin (BTC), Ethereum (ETH), Ethereum classic (ETC), Litecoin (LTC) and the US dollar (USD). While the average relative tick size spread increased 380-fold, the spreads are still largely unconstrained providing a unique setting to test whether traders switch from market orders to limit orders due to the reduced probability of undercutting, quoted depth increases and spreads decline post the tick size increase, as predicted by Werner et al. (2015). Our dataset also provides an opportunity to verify the theoretical prediction of a convex relationship between trading costs and tick size and thus confirm empirically that the optimal tick size is strictly greater than zero. Although our focus is on a cryptocurrency exchange due to data limitations in the equity markets, our findings are equally applicable to other markets. Kraken's market structure resembles modern equity markets with continuous trading via a limit order book without intermediaries, satisfying the market structure assumptions of Foucault et al. (2005) and Goettler et al. (2005). Traders can either execute immediately with a market order or wait for a better execution price with a limit order. Limit orders are stored in the limit order book and are executed according to price priority.

Extant literature provides ample evidence of enhanced market quality from progressive decreases in tick sizes because of historic shift to decimalization and more recent competitive pressure from other trading venues across exchanges in North America (Bacidore, 1997; Goldstein and Kavajecz, 2000; Harris, 1991, 1994; Porter and Weaver, 1997), Europe (Bourghelle and Declerck, 2004; Meling and Odegaard, 2017), and Asia (Aitken and Comerton-Forde, 2006; Lau and McInish, 1995). These improvements in market quality are consistent with the reduction in indirect trading costs associated with bid-ask spread outweighing the increased cost of enforcing time and price priority due to undercutting.

By contrast, there is little empirical evidence to demonstrate the trade-off identified by theoretical models and show that under sufficiently small tick sizes, the benefits of reducing transaction costs may not sufficiently compensate for the increased incidence of undercutting.

Moreover, there is limited empirical evidence that demonstrates the predicted convex shape relationship between trading cost and tick size and shows substantial improvement in market quality due to an increase in tick size. The pricing grid on most exchanges is generally too coarse and widespread increases in tick sizes on exchanges are extremely rare.

A notable exception is the NYSE two-year pilot study commissioned in 2016 which raised the trading increment from once cent to five cents for a subset of mainly small illiquid stocks to assess whether widening the tick size would enhance the market quality of these stocks. While early evidence from the trial is largely inconclusive with increase in trading costs for retail-sized transactions but potential benefits for institutional-sized trades, Rindi and Werner (2017) note a small decline in spreads for unconstrained stocks. Considering the argument of Seppi (1997) that the optimal tick size is higher for institutional traders than retail traders, these results suggest that the optimal tick size for the pilot stocks exceeds five cents for unconstrained stocks and institutional traders but is smaller than five cents for constrained stocks and retail traders. Prior to the tick size pilot on NYSE, Euronext also increased the tick size for a subset of stocks listed on its Paris Bourse to reduce execution costs and improve market quality. Bourghelle and Declerck (2004) investigate the changes for these largely unconstrained stocks but fail to observe any significant change in the relative, quoted and effective spread.

Another potential reason for the scarcity of widespread tick size increases across exchanges is that relative tick size (tick size relative to the stock price), which is arguably a more meaningful economic measure of transaction costs (O'Hara et al., 2018), can be adjusted by firms without changes to the absolute tick size. Angel (1997) observes a large variability in the tick size rules across equity markets but a fairly constant relative tick size, suggesting that firms do not always desire a smaller tick size, but rather aim to maintain the relative tick size within a preferred range to optimize liquidity for investors. If the relative tick size becomes too small or too large, a firm can undertake a stock split or a reverse stock split and change the tick size to a more desired level (Angel, 1997, Conroy, Harris and Benet, 1990; Gray, Tom and Whaley, 2003; Schultz, 2000). It follows that adjusting relative tick size to a more optimal level should thus lead to an improvement in market quality. However, literature documents strong evidence of increased trading costs (Schultz, 2000; Gray et al., 2003) and volatility (Angel, Brooks and Mathew, 2004; Koski, 1998) following stock splits suggesting that larger relative tick sizes reduce market quality. Since splitting firms are usually substantially larger and more liquid than typical listed firms, these counterintuitive results may be the result of higher liquidity and larger proportion of constrained stocks in the sample.

Using high frequency trade and quote data, we find that widening the tick size on Kraken encourages traders to post more and larger limit orders, increasing the overall cumulative depth of the limit order book. Limit orders posted at the same price point increase, suggesting that liquidity providers are clustering limit orders at the same price levels, restoring the relevance of time priority. The improved liquidity environment also increases the size of liquidity demanding orders. These results indicate that Kraken's tick size increases lead to a change in the traders' behavior as the increased execution probability from aggressive undercutting no longer compensates traders for the larger reduction in execution price attained by posting orders closer to the best bid and offer. An analysis of spreads confirms that increase in tick size in unconstrained markets leads to lower transaction costs with a 14.74 basis points (bps), 10.88 bps and 12.01 bps reduction in quoted, effective and realized spreads, respectively. Our results thus empirically verify the theoretical predictions of Foucault et al. (2005) and Werner et al. (2015) that when spreads are unconstrained and the tick size is very small, increasing the tick size reduces spreads, as it forces traders to improve the price by a larger amount. Consistent with the theoretical convex relationship between relative tick size and spreads, currency pair with highest (smallest) relative tick size increase exhibits a larger (smaller) reduction in spreads. Moreover, in contrast to Rindi and Werner (2017) where benefits in tick size increases mainly accrue to institutional traders, we find a reduction in spreads across both retail and institutional sized trades. Finally, we show that the increased tick size also improves market quality by reducing the midpoint return volatility.

Overall, our findings demonstrate that when tick sizes are close to zero, spreads are unconstrained, and undercutting is prevalent, a larger tick size can improve liquidity provision and market quality. These results confirm that optimal tick size is positive and are consistent with a convex relationship between tick size and quoted spread hypothesized by literature. Our findings have implications for equity market design and the setting of minimum tick sizes by exchanges. These results provide support for a dynamic minimum tick size based on the share price and liquidity of the stock rather than constant tick size for all stocks. While many exchanges already determine the minimum tick size based on a step function linked to the share price, US exchanges are waiting on the outcome of the US pilot program to make any decisions regarding minimum increments. The results also highlight the issues faced by traders in the cryptocurrency markets at a critical point in their development, by showing how the market structure impacts trader behavior. Our work also has wider potential implications for other markets with an environment of exceedingly granular tick sizes, such as foreign exchange markets, where order flow is the primary determinant of daily price fluctuations (Baillie & Bollerslev, 1990; Breedon & Ranaldo, 2013; Ranaldo, 2009).

The remainder of this paper is structured as follows. Section 2 describes the data collection and research design. The results of the tick size increase are presented in section 3 whilst section 4 concludes.

2 Research design

2.1 Data

Kraken increased the tick size on two occasions on August 30th and September 6th, 2017 at 06:00, see Table 1.[2] The relative tick size across currency pairs prior to the tick size increase ranges from 0.0015 bps (LTC-USD) to 0.133 bps (ETH-BTC), which is significantly lower than the smallest relative tick size of 2.2 bps across 22 equity exchanges (median of 25.9 bps) reported by Angel (1997). The tick size increase was substantial for some of the currency pairs. For example, LTC-USD increased from 1E-05 (0.0015 bps) to 1E-02 (1.4867 bps) which is a 99,900% increase. After the tick size increase the relative range increases to between 0.2261 bps (BTC-USD) and 2.6517 bps (ETC-BTC), bringing Kraken into line with competing venues such as Gemini and Gdax.

< Table 1 here >

The unique dataset of high-frequency order-level data obtained directly from Kraken's Application Programming Interface (API). The API is polled twice a second to get a snapshot of the top ten levels of the order book. These snapshots are used to construct a standard trade and quote dataset instead of reported quote updates and trades. Due to the short period between the two successive tick size changes, we eliminate the week in between and collapse the tick size changes into one event. We consider a period one month before and after the tick size increase, from 1st August, 2017 to 5th October, 2017 and investigate the currency pairs Bitcoin to US Dollar (BTC-USD), Ethereum to Bitcoin (ETH-BTC), Litecoin to US Dollar (LTC-USD), Ethereum-Classic to US Dollar (ETC-USD), Ethereum-Classic to Ethereum

[2] On each of the days where the tick size was increased, 46 currency pairs were affected. The same currency pairs were not necessarily affected by both changes. The analysis is limited to six currencies due to data availability.

(ETC-ETH) and Ethereum-Classic to Bitcoin (ETC-BTC).[3] Trades and quotes are time stamped to the millisecond and recorded in UTC time, with an indicator provided for trade initiator.

Trade aggregation is complicated by Kraken's relatively slow matching engine, resulting in trades not being time stamped with the exact same millisecond when executing as a part of one market order. Appendix A1 documents the time distribution between trades and analyses the adjustment needed for trade aggregation. We find that the central messaging engine delays consecutive interactions of market orders with limit orders by up to 20 milliseconds, with such a filter capturing 80% of the observed trade durations. As such, trades which occur within 20 milliseconds of each other in the same direction (buy or sell) are considered as one market order. Trade volumes are then aggregated and assigned the average price and total volume of the trade.

2.2 Trading behavior metrics

Since spreads are not a sufficient statistic for market quality (Jones and Lipson, 2001), we use a battery of measures to capture trading behavior, trading costs and liquidity. Furthermore, given that small tick sizes allow traders to undercut standing limit orders to gain execution priority, we introduce novel set of metrics to measure and analyze this trading behavior. All metrics are averaged over 15-minute buckets per pair.

$Order\ exposure$ measures undercutting by calculating how many seconds a limit order (bid or ask) is exposed for at the best on average. The measure indicates the stability of the best prices and is inversely related to undercutting behavior.

$Limit\ order\ volume$ measures the average unit volume (BTC, ETH, ETC, LTC) of each limit order. $Market\ order\ volume$ measures the average unit volume in a market order. $Limit\ order/Market\ order$ measures the number of limit orders per market order to determine if more limit orders are posted.

As the tick size is very small it is uncommon to see more than one limit order placed at the same price step. We cannot observe how many orders are posted at each price step without a market order executing, as we only observe aggregated volume. $Resting\ limit\ orders$

[3] Obvious pricing errors were corrected (eg misplacement of decimal points surrounding the tick size changes). Kraken was offline for one hour on August 25 and an hour and a half on August 26 due to maintenance during which time there are no quotes or trades observed.

measure how many limit orders within a trade are resting at the same price step. To make sure that we count all limit orders within a price step we exclude trades that execute against only one limit order and also exclude the last price step of a market order that executes against multiple price steps.

$Price\ Differential$ measures the average price difference of executed limit orders within each market order following Eq. (1):

$$Price\ Difference_{jit} = Max\ Price_{jit} - Min\ Price_{jit} \tag{1}$$

where $Price\ Difference_{ijt}$ is the difference between the maximum price and minimum price of limit orders in market order j for currency pair i at time t.

$Price\ steps\ per\ market\ order$ counts how many price steps a market order goes through, indicating the degree to which market orders walk the book and execute against multiple price levels.

These trading behavior metrics indicate if the tick size increase is successful at attracting more liquidity providers who post larger limit orders, consolidating depth at fewer price steps and stabilizing the best quotes by letting them stand for longer.

2.3 Liquidity metrics

We explore the effect of the tick size changes on several liquidity measurements. Relative quoted spread measures the cost of a small round-trip trade calculated using Eq. (2):

$$Relative\ Quoted\ Spread_{it} = \frac{(Ask_{it} - Bid_{it})}{m_{it}}$$

(2)

where Ask_{it} and Bid_{it} are the best ask and bid quotes at time t for currency pair i and the midpoint at time t is $m_{it} = (Ask_{it} + Bid_{it})/2$. Quoted spread is time weighted.

The variable *constrained* measures the proportion of time the spread is equal to one tick, represented as a percentage of the 15-minute bucket. If the spread is constrained for the entire 15 minutes, the variable takes the value of 100%.

The volume weighted effective spread captures the cost of liquidity when it is demanded, and is calculated using Eq. (3).

$$Effective\ Spread_{it} = 2q_{it}(P_{it} - m_{it})/m_{it} \tag{3}$$

where q_{it} is the direction of the trade, taking +1 for a buyer and -1 for a seller initiated order. P_{it} is the price of the trade at time t for currency pair i. m_{it} is the midpoint at time t. The volume weighted realized spread captures the returns to liquidity provision, and is calculated using Eq. (4).

$$Realized\ Spread_{it} = 2q_{it}(P_{it} - m_{it+Xmin})/m_{it} \quad (4)$$

where the trade price, P_{it}, is compared to the midpoint after the price impact has been realized $m_{it+Xmin}$.[4] The difference between the effective spread and the realized spread is the price impact which also follows Eq. (5). The price impact shows the subsequent price change following a trade.

$$Price\ Impact_{it} = 2q_t \frac{(m_{it+X} - m_{it})}{m_{it}} \quad (5)$$

Where q_{it} is the direction of the trade, taking +1 for a buyer and -1 for a seller initiated order. m_{it+X} is the lead midpoint for currency pair i and follows the lead time specified when calculating the realized spread. m_{it} is the midpoint at time t for currency pair i. The price impact is volume weighted.

The time weighted quoted depth at the best bid and offer is calculated following Eq. (6). Depth at best is converted to USD for non USD based currency pairs.

$$Depth_{it} = Best\ bid\ price_{it} * Bid\ size_{it} + Best\ ask\ price_{it} * Ask\ size_{it} \quad (6)$$

To estimate the effect on the lower level depth we employ the measure constructed in Van Kervel (2015) shown in Eq. (7) - (9). We use this measure, as summing the dollar volume depth of the top five levels for example will be affected mechanically by the tick size change. As the tick sizes are now larger, liquidity has to consolidate on to fewer price levels. However, this effect is mechanical and is not informative about whether additional dollar volume entered the book following the change. The metric proposed by Van Kervel (2015) measures the dollar volume depth available at X bps points on either side of the midpoint. The measure is therefore not affected mechanically by the tick size increase and is a better measure of lower level depth. The depth metric is calculated in USD.

$$Depth\ Ask(X)_{it} = \sum_{i=1}^{I} P_{i,t}^{Ask} Q_{i,t}^{Ask} 1\left(P_{i,t}^{Ask} < m_{it}(1+X)\right) \quad (7)$$

[4] The lead time of the midpoint is estimated for each currency pair as we cannot expect this market to follow equity markets. ETC-BTC, ETC-ETH and ETH-BTC are compared to the midpoint after 10 seconds and LTC-USD, BTC-USD and ETC-USD after 20 seconds. Further details on the VAR model and results are provided in Appendix A2.

$$Depth\ Bid(X)_{it} = \sum_{i=1}^{I} P_{i,t}^{Bid} Q_{i,t}^{Bid} 1\left(P_{i,t}^{Bid} < m_{it}(1+X)\right) \tag{8}$$

$$Depth\ at\ (X)\ bps_{it} = Depth\ Ask(X)_{it} + Depth\ Bid(X)_{it} \tag{9}$$

where $P_{i,t}^{Ask}$ is the ask price for currency pair i at time t, $Q_{i,t}^{Ask}$ is the ask quantity, m_{it} is the midpoint and X is the basis point cut off. The cutoff varies between currency pairs to reflect their varying levels of liquidity.[5] The bps cutoff (X) is determined by calculating the distance between the midpoint and prices at level 1 and level 9 depth. Then we take the average between the 90th percentile of level 1 and 10th Percentile of level 9 throughout the sample period to ensure that the cutoff captures level 1 most often and rarely goes beyond level 9.

Volatility is measured as the standard deviation of midpoint returns using Eq. (10):

$$Short - term\ volatility_{it} = SD\left(\frac{(m_{it} - m_{it-1})}{m_{it-1}} * 10{,}000\right)$$

(10)

where m_{it} is the midpoint for currency i at time t and m_{it-1} is the preceding midpoint. The return is calculated in bps before calculating the standard deviation.

2.4 Econometric specification

To analyze the effects of the tick size increase on market quality and to test the theoretical relation between the relative tick size and spreads we avail of a two stage least squared model, which enables us to use the relative tick size, the tick size relative to the price, as the shock variable in the model. Using the relative tick size in our specification is central as Harris (1994, 1996, 1997) argues that the absolute tick size in cents does not affect trading behavior. The relative tick size is what affects the trading behavior, as it gives more information about the dollar value of the tick size and the relative cost of the tick size to the trader. However, the tick size has a mechanical effect on liquidity metrics calculated from quotes, as it defines the values the quotes can have. Including the relative tick as the independent variable representing the shock will therefore subject the model to endogeneity issues. We therefore use a two stage least squares model with the percentage change of the tick size as the instrument following Eq. (11). The percentage change of the tick size directly affects the relative tick size but has no direct effect on the trading behavior or liquidity metrics included as dependent variables. The F-statistic of the first stage regression with

[5] The currency pairs take the following values for X: ETH-BTC = 22 bps, LTC-USD = 39 bps, BTC-USD = 13 bps, ETC-ETH = 102 bps, ETC-USD = 66 bps, and ETC-BTC = 99 bps.

currency pair fixed effects (68.39 - 78.03) varies depending on the number of observations but all statistics are above the critical values specified by Stock and Yogo (2005) which allows us to reject the null of a weak instrument. The second stage includes the estimated variable $\widehat{Relative}\,Tick_{it}$ as an independent variable which is the variable of interest in Eq. (12).

$$Relative\ Tick_{it} = \alpha_i + \beta_1 PercentChange_{it} + \beta_2 \$Volume_{it} + \beta_3 Trades_{it}$$

$$+\beta_4 Volatility_{it} + \beta_5 MeanPrice_{it} + \varepsilon_t \qquad (11)$$

$$Metric_{it} = \alpha_i + \beta_1 \$Volume_{it} + \beta_2 Trades_{it} + \beta_3 Volatility_{it} + \beta_4 MeanPrice_{it}$$

$$+\beta_5 \widehat{Relative}Tick_{it} + \varepsilon_t \qquad (12)$$

The $Relative\ Tick_{it}$ is the tick size relative to the price in basis points for currency pair i in 15-minute interval t, α_i is currency pair fixed effects, $PercentChange_{it}$ is the percent change in the tick size which takes the value of zero before the first increase and the actual percentage change of the tick size after the second tick size increase. We ignore the week in between the tick size changes and treat the two events as one as the second tick size increase was announced when the first was implemented on August 30th, 2017. We can therefore not confidently treat the two events as independent. $\$Volume_{it}$ is the dollar volume in base currency, $Trades_{it}$ is the number of trades, $Volatility_{it}$ is the currency pair 15-minute high-low price range divided by the sum over two, $MeanPrice_{it}$ is the average price in base currency and ε_t is the error term. The event window is approximately one month (29.25 days) on either side of the event as our dataset starts on August 1st and the first tick size change took effect at 06:00 UTC time. The time horizon allows for new customers to react to the tick size change as Kraken is subject to "know your customer" regulation which can delay registration by a week. Using one month on either side of the event therefore allows us to capture the full effect as it is unlikely to be immediate.

The model is estimated in aggregate for several reasons. First, the currency pairs in the dataset are different in trading volume and three pairs are cross rates between cryptocurrencies and three pairs are exchange rates to the US dollar. Given the difference in these currency pairs we take advantage of the panel data and include currency pair fixed effects to allow for variation in the intercept between pairs. We can thereby control for the unobservable time invariant differences in currency pair characteristics. Second, we include all six currency pairs in the panel regression rather than estimating the effects on the individual currency pairs to increase the number of observations and allow for more robust results.

3 Empirical results

The currency pairs in our sample differ significantly in terms of trading activity and overall liquidity. Table 2 shows summary statistics for trading behavior, liquidity metrics and control variables for the most traded currency pair (BTC-USD) and the least traded fiat pair (ETC-USD). Summary statistics for the remaining pairs are available in Appendix A3. The average daily number of trades is significantly higher for BTC-USD (at over 11,000) than for ETC-USD (with just over 1,500 trades daily). Given the higher trading activity in Bitcoin, the average order exposure time is also shorter. The average market and limit order volume are also higher for BTC-USD, however, only 1.49 limit orders are posted at the same price point on average for BTC-USD versus 1.17 for ETC-USD. This is one of the central issues of unconstrained markets as liquidity providers do not post orders to the same price step, but rather create new price steps by undercutting the price by a single tick. It is not uncommon to observe best prices with little volume at prices marginally better than a larger order at lower levels on Kraken. This results in an average depth at the best prices being just over $21,470 for BTC and just under $5,000 for ETC. Undercutting in the cryptocurrency markets may be exacerbated by their limited or no fundamental value (Cheah and Fry, 2015), largely constraining price-moving information to that contained in order flow. This hypothesis is supported by Buti et al. (2015) who argue that undercutting traders do not have strong opinions about the fundamental value, but rather trade opportunistically to profit from small deviations in the price from the average valuation.

< Table 2 here >

Transaction costs can vary widely between currency pairs, where BTC has an average quoted spread of 8.6 bps (which is below most equity markets), ETC has an average quoted spread of 77 bps. The spreads are rarely constrained, with BTC-USD being constrained at most 8.71% of the day over the sample period. Most trades experience low transaction costs, but larger trades can incur significant transaction costs when they ‘walk the book’. This is visible when comparing the quoted and effective spread. The effective spread, or the average cost of a trade, is 15.1 bps for BTC-USD but increases to 78 bps for ETC-USD.

Figure 1 plots the average relative tick size versus the average relative quoted spread for the six pairs pre and post the tick size increase along with the S&P500 index constituents for comparison. The graph illustrates that the relative tick sizes for all six currency pairs in the pre-event period are significantly lower than any of the index constituents. Following the tick size increases, the relative tick sizes are comparable to the average relative tick size of the firms in the index. Moreover, while the spreads of the S&P500 index constituents become largely constrained once the relative tick sizes exceed approximately 4 bps, the relative quoted spreads of the six currency pairs listed on Kraken are completely unconstrained. The high level of dispersion around the level of spread constraint in the equity markets shown in Figure 1 explains the lack of consensus regarding market quality improvements from the US pilot study. While the figure depicts considerable dispersion in relative quoted spreads for unconstrained stocks, it highlights the predicted convex shape between relative tick size and relative spread. The inclusion of cryptocurrency pairs provides additional observations beyond the smallest relative tick size observed in the equity market. The plot confirms relative quoted spreads continue to increase as relative tick size approaches zero.

< Figure 1 here >

Figure 2 shows that on average you can trade between $500 and $1,000 on Kraken within the best ten price levels most of the time, but as you trade larger quantities there is insufficient depth for most currency pairs. This indicates that the market is sufficiently deep for retail investors but perhaps too costly for institutional investors.

< Figure 2 here >

Table 3 provides a univariate comparison of liquidity and trading behavior metrics around the tick size increase on Kraken. The results indicate that the excessive activity caused by undercutting is reduced after the tick size increase with an increase in the average order exposure time by 29%. The number of trades per day decreases by 31%, but the size of individual market and limit orders increases by 9.7% and 14%, respectively following the tick size, increase suggesting there are fewer, larger trades in the post period. The ratio of limit orders to market orders also increases slightly, consistent with more passive liquidity and an increase in the number of resting limit orders per price step. This suggests that traders post more, larger limit orders, and cluster them at fewer price steps. Quoted, effective and realized spreads all decline significantly. While the proportion of time spreads are constrained increases from 5.3% to 8.2%, the spreads are still largely unconstrained post the tick size increase as shown in Figure 1.

< Table 3 here >

As the effect of a tick size change depends on the relative tick size (Aitken & Comerton-forde, 2006; Angel, 1997), we use the relative tick size as an instrumental variable in a two-stage least squared regression to account for potential endogeneity. The first column of Table 4 reports the first stage results which controls for variation in the dollar volume, trading activity, volatility and average price between currency pairs. $PercentChange_{it}$ takes a value of zero prior to the tick size increase, and the percent change in the tick size after. The F-statistic of the regression is 69.27 which rejects the null hypothesis of a weak instrument using the critical values by Stock and Yogo (2003).

< Table 4 here >

The remaining columns of Table 4 report the regression results of the impact of tick size increase on trading behavior. Prior to the tick size change it was rare to observe more than two orders at the same price, as traders enjoyed price priority with inconsequential price improvement. Following the tick size increase, we observe price clustering of limit orders as traders disperse their orders across fewer price steps. We find the average limit order increases by just over one unit (column 2) and there are more limit orders being posted at the same price point (column 3). This result indicates an improved average trading price for large volume orders and is consistent with the increased liquidity provision arguments of Harris (1997). Both coefficients are significant at the one percent level of significance.

Since reduced undercutting improves liquidity provision, it is also likely to affect the behavior of liquidity demanding traders. Given the extremely small tick size on Kraken, large orders frequently 'walk the book', executing against limit orders at multiple price points. This supports the theory by Werner et al. (2015) who document that for illiquid stocks with small tick sizes and frequent undercutting, spreads widen and traders use market orders instead of limit orders, incurring higher trading costs. Consistent with this prediction, we find that a tick size increase reverses this effect with market order volume increasing by 1.756 units (column 4), significant at the five percent level. We also find evidence of more limit orders at the same price points leading to market orders executing against fewer price steps (column 5), significant at the one percent level. Overall, these results indicate that tick size increases on Kraken lead to a change in the traders' behavior with reduced instances of undercutting, increased use of limit orders and an overall increase in volume.

Table 5 shows the impact of Kraken's tick size increase on trading costs over the one-month pre and post event window. While tick size has a mechanical effect on spreads, its direct effect is less certain when spreads are unconstrained. Evidence from stock splits shows that tick sizes increases lead to wider spreads. However, Foucault et al. (2005) and Werner et al. (2015) predict that increasing the tick size of unconstrained stocks will lead to increased liquidity provision and lower spreads. While Rindi and Werner (2017) find that this holds for quoted spreads, effective spreads barely changed when the tick size increased from one cent to five cents in the US pilot study. Similarly, Bourgelle and Declerck (2004) find little effect on spreads from tick sizes increases on the Paris Bourse. In the case of Kraken, none of the currency pairs are tick constrained prior to the tick size increase and the relative tick size is also extremely small. Consequently, we find the increase in small tick sizes on Kraken provides strong empirical evidence in support of the theoretical models. We observe that quoted, effective and realized spread decrease by 14.7, 10.9 and 12.0 bps, respectively (column 1 to 3). Furthermore, spreads improve for both retail and institutional-sized trades with the effective spread of a hypothetical \$500 and \$200,000 trade decreasing by 18.15 bps and 28.64%, respectively (column 4 and 5). All coefficients are significant at the one percent level. These results confirm that while institutions trading large blocks have a larger optimal tick size than small retail investors (Seppi, 1997), both prefer a tick size strictly greater than zero.

As the incentive to post limit orders is affected by a tick size change, the quoted depth at the best bid and offer is also likely to be affected. Tick size increases have resulted in more depth at the best prices (Conroy et al., 1990; Gray et al., 2003; Schultz, 2000) so a tick size increase at Kraken is expected to have the same effect and consolidate depth at the best prices, reducing execution costs for large trades. Combined with the findings of Goldstein and Kavajecz (2000) that a tick size decrease leads to a reduction in cumulative depth we expect that a tick size increase will increase both the depth at best and cumulative depth. While we do not find evidence of a change in depth at best (column 6), the cumulative depth (depth at X) increases by 16.85 bps (column 7), significant at the one percent level. This result is consistent with Rindi and Werner (2017). This result indicates that following the tick size increase liquidity is not just concentrated at fewer levels as expected, but depth increases throughout the entire order book.

Finally, tick size changes affect the precision of prices, impacting short-term volatility, but the direction of the effect is unclear. Both Angel et al. (2004) and Koski (1998) find a significant increase in volatility following widening of relative tick sizes from stock-splits as a result of increased participation of small-volume traders in the market. By contrast, we observe a 23.5% decrease in midpoint return volatility, significant at the one percent level (column 8). We attribute this result to the additional depth in the order book coupled with larger order volume and reduction in excessive trading activity from undercutting increases price stability. Overall, our results suggest that the increase in tick sizes on Kraken improve both market quality and pricing efficiency by encouraging traders to enter more, larger liquidity providing orders.

< Table 5 here >

For robustness, Table 6 compares two currency pairs with the smallest and the largest relative tick size increase (BTC-USD vs ETC-BTC). We find that while all spreads decrease for both subsamples, the larger tick size change leads to a more pronounced effect with a 15.56 bps reduction in spread vs 9.84 bps for the smallest tick size change, consistent with a convex shape relationship between tick size and spread proposed by literature. Both coefficients are significant at the one percent level. As the quoted spreads post the tick size increase is still 31 ticks for BTC-USD and 23 ticks for ETC-USD on average (Table 2 and Appendix A2), it is likely the quoted, effective and realized spreads on Kraken could be decreased further by widening the tick size until quoted spreads become more constrained.

< Table 6 here >

4 Conclusion

We investigate the importance of tick sizes in a setting unique to the cryptocurrency market with significantly unconstrained spreads, extremely small tick sizes and limited fundamental value. We examine how a tick size increase in this market structure affects undercutting behavior and market quality. Using novel trading behavior metrics constructed specifically for this task we find an improvement in liquidity provision, with more, larger limit orders submitted at each price point. This is consistent with Harris' (1996) argument that larger tick sizes will increase quoted volume.

Additionally, we find that spreads improve after the tick size increase, consistent with the model developed by Foucault et al. (2005). When tick sizes are very small, liquidity providers cannot improve the spread substantially which disincentivizes price improvement. Given a wide enough spread, an increased tick size rewards price improvement. This shows that exceedingly small tick sizes can be detrimental to market quality by facilitating undercutting, essentially rendering time priority redundant. Larger tick sizes are also found to improve depth and reduce volatility, suggesting smaller tick sizes facilitate increased transitory volatility due to undercutting.

Our findings have implications for market design. We show that exceedingly small tick sizes are undesirable and can be detrimental to market quality. This has relevance for equity markets, which have seen tick sizes consistently reduce over the last 20 years. Our findings have particular implications for cryptocurrency and foreign exchange markets, which operate with extremely small tick sizes. As such we add to the debate surrounding optimal tick sizes, particularly focusing on how the change in tick sizes impacts trader behavior.

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Figure 1
Comparison of relative tick sizes and relative quoted spreads across Kraken and S&P500 stocks

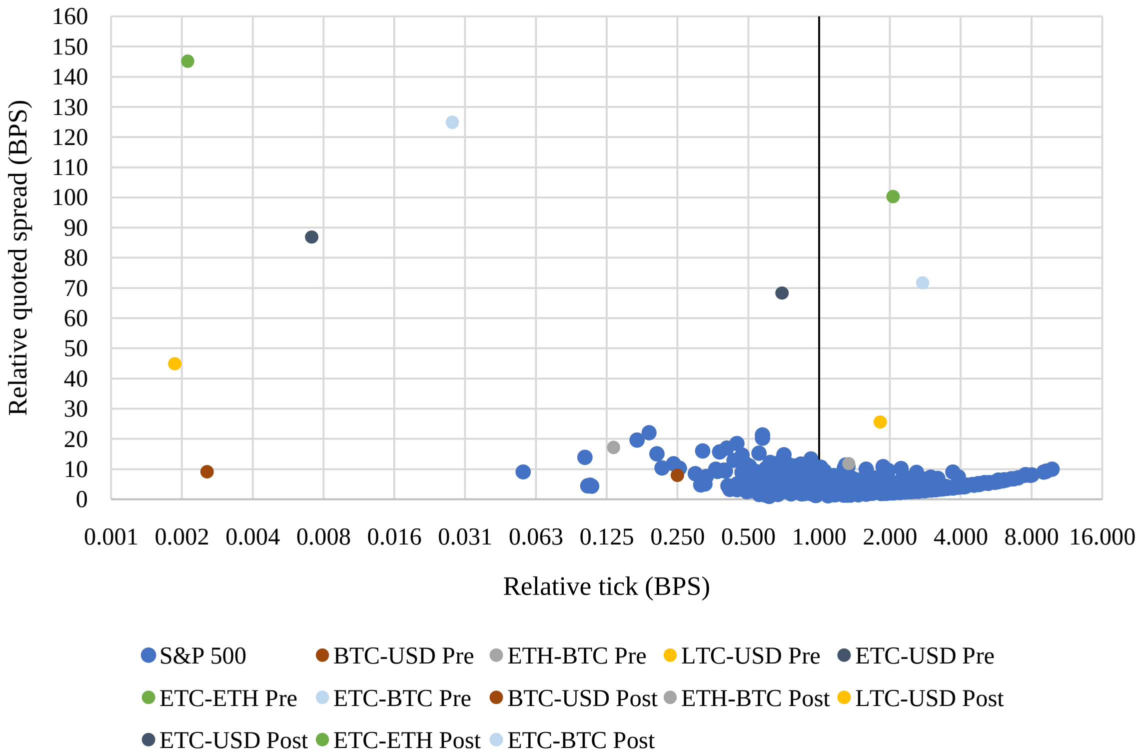


Figure 2
Depth available subject to trade shocks

The figure shows how often the bid or ask side can absorb different dollar volume trade shocks. All currency pairs are converted into USD. The shock measure is time weighted and average across the period 1st August 2017 to 5th October 2017.

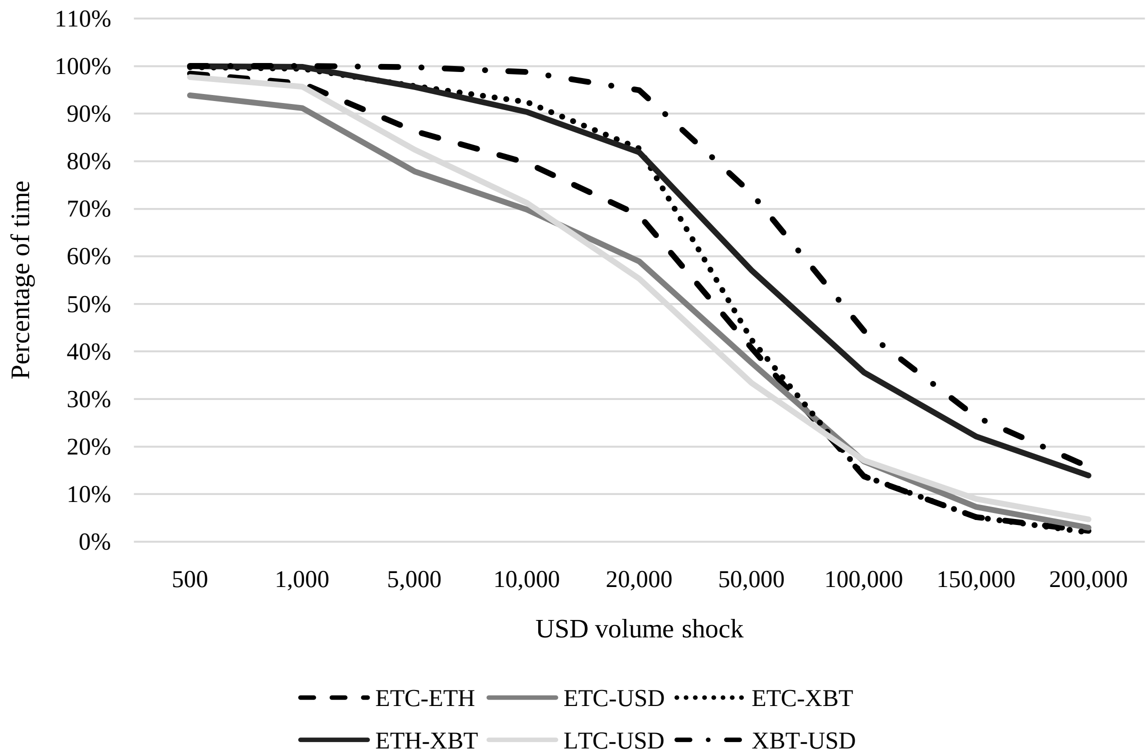


Table 1
Currency pairs and tick sizes at Kraken

The tick sizes are presented in decimal places and in basis points (bps) relative to the average daily price in the sample period 23rd August to 13th September 2017.

	Pre 30 August		Post 30 August		Post 6 September	
Currency pair	Tick	Bps	Tick	Bps	Tick	Bps
BTC-USD	1E-03	0.0023	1E-02	0.0226	1E-01	0.2261
ETH-BTC	1E-06	0.1330	1E-06	0.1330	1E-05	1.3297
LTC-USD	1E-05	0.0015	1E-04	0.0149	1E-02	1.4867
ETC-ETH	1E-08	0.0020	1E-06	0.1984	1E-05	1.9841
ETC-USD	1E-05	0.0060	1E-04	0.0598	1E-03	0.5882
ETC-BTC	1E-08	0.0265	1E-06	2.6517	1E-06	2.6517

Table 2
Summary statistics of trading behavior and liquidity metrics

The table shows summary statistics of trading behavior, liquidity and control variables for BTC-USD and ETC-USD over the period 1st August to 5th October 2017on Kraken. All metrics are daily averages. $Order\ exposure$ is the number of seconds the best bid or ask order is exposed. $Limit\ order\ /\ market\ order$ shows the proportion of limit orders to market orders. The $average\ market\ order\ and\ limit\ order\ volume$ shows the volume in BTC or ETC. The $average\ price\ difference$ is the difference between limit order prices within a market order scaled by 100. The $average\ price\ steps$ is how many price steps a market order goes through on average. The $number\ of\ resting\ limit\ orders$ shows how many limit orders are resting at the same price step on average. $Quoted\ spread$ is time weighted and in basis points. $Effective\ and\ realized\ spread\ and\ price\ impact$ are volume weighted and in basis points. $Constrained$ is the percent of the day where the spread is equal to one tick. $Quoted\ spread\ (ticks)$ shows the pre and post change quoted spread in number of ticks time weighted. $Depth\ at\ best$ and $depth\ at\ X\ bps$ sums the USD depth at X bps on either side of the midpoint where X takes the value of 13 basis points for BTC-USD and 66 basis points for ETC-USD. $Short-term\ volatility$ is the average 15-minute midpoint return volatility. $Effective\ spread$ \$500 and \$200K estimates the effective spread in bps of a hypothetical trade of a dollar volume. The $number\ of\ trades$ is the daily total. $Dollar\ volume$ is the daily total displayed in 10,000 USD. $Volatility$ is the currency-time high-low price range divided by the sum over two in basis points. The $mean\ price$ shows the average price in USD. The $relative\ tick$ is the tick size in cents over the price and averaged in the 15-minute buckets.

	BTC-USD					ETC-USD				
	Mean	Median	Std	Minimum	Maximum	Mean	Median	Std	Minimum	Maximum
Panel 1: Trading behavior metrics										
$Order\ exposure\ (seconds)$	12.04	11.24	7.06	8.38	67.10	28.61	24.83	16.32	8.85	101.32
$Limit\ order\ /\ market\ order$	1.71	1.74	0.15	1.23	1.95	1.88	1.86	0.26	1.24	2.61
$Average\ market\ order\ volume$	0.53	0.51	0.13	0.26	0.87	37.15	33.96	20.73	5.46	109.61
$Average\ limit\ order\ volume$	0.29	0.29	0.06	0.17	0.46	18.02	16.83	8.57	3.09	45.70
$Average\ price\ difference\ (scaled)$	42.49	41.29	18.00	12.82	97.24	0.59	0.53	0.34	0.19	2.24
$Average\ price\ steps$	1.28	1.28	0.06	1.09	1.37	1.58	1.57	0.17	1.17	1.91
$Number\ of\ resting\ limit\ orders$	1.49	1.48	0.09	1.33	1.68	1.17	1.16	0.07	1.04	1.31
Panel 2: Liquidity metrics										
$Quoted\ spread\ (bps)$	8.63	7.94	4.07	3.81	31.76	77.25	76.83	28.56	38.25	237.84
$Effective\ spread\ (bps)$	15.11	13.29	6.37	7.19	34.60	77.98	71.32	30.25	41.31	252.00
Realized spread (bps)	12.67	11.40	5.60	5.33	33.35	69.85	61.18	29.56	36.58	247.15
$Price\ impact\ (bps)$	2.44	1.55	2.40	-0.07	13.07	8.13	6.70	5.54	-1.52	23.89
$Constrained$ (%)	8.71	8.14	3.61	3.48	16.36	2.62	2.62	1.52	0.16	6.75
$Quoted\ spread\ (pre\ ticks)$	3,482.02	3,271.69	2,125.78	1,521.44	12,997.65	12,808.44	12,291.79	4,353.18	8,044.14	32,152.47
$Quoted\ spread\ (post\ ticks)$	31.43	29.02	9.53	16.24	53.61	85.96	80.17	31.14	46.15	146.10
$Effective\ spread$ \$500 (bps)	10.43	9.60	4.60	4.53	34.28	120.06	118.31	39.43	68.22	345.69
$Effective\ spread$ \$200K (bps)	440.44	139.46	2,378.68	59.41	19,463.76	12,228.36	10,028.51	10,761.75	929.74	45,177.81
$Depth\ at\ best\ (1{,}000\ USD)$	21.47	19.98	8.07	10.57	55.98	4.95	4.50	2.64	1.04	14.33
$Depth\ at\ X\ bps\ (1{,}000\ USD)$	171.98	159.98	57.70	84.45	364.62	99.44	89.77	62.19	12.87	352.81
$Short-term\ volatility$	1.94	1.84	0.86	0.77	4.80	4.27	3.64	2.27	1.60	10.48
Panel 3: Control variables										
$Number\ of\ trades$	11,360.47	11,146.00	4,130.66	4,113.00	23,715.00	1,555.11	1,179.00	1,104.40	383.00	5,026.00
$Dollar\ volume\ (10{,}000\ USD)$	2,523.51	2,094.78	1,203.09	975.49	7,435.43	89.12	51.29	101.09	9.05	472.34
$Volatility\ (bps)$	63.47	54.02	31.04	26.71	196.67	82.37	64.05	50.17	21.70	286.86
$Mean\ price$	4,004.88	4,160.71	494.61	2,712.59	4,806.65	14.36	14.29	2.36	10.17	20.57
$Relative\ tick\ (bps)$	0.12	0.02	0.12	0.00	0.29	0.37	0.05	0.40	0.01	0.98

Table 3

Difference in mean and median market quality metrics

This table reports the mean and median liquidity and trading behavior measures in 15 minute buckets in the month before the first change and the month after the second tick size increase across currency pairs. The metrics are then calculated across the six currency pairs. $Order\ exposure$ is the number of seconds the best bid or ask order is exposed. The $number\ of\ trades$ is the daily total. $Limit\ order\ /\ market\ order$ shows the proportion of limit orders to market orders. The $average\ market\ order\ and\ limit\ order\ volume$ shows the volume in USD. The $average\ price\ difference$ is the difference between limit order prices within a market order scaled by 100. The $average\ price\ steps$ is how many price steps a market order goes through on average. The $number\ of\ resting\ limit\ orders$ shows how many limit orders are resting at the same price step on average. $Dollar\ volume$ is the daily total displayed in 10,000 USD. $Quoted\ spread$ is time weighted and in basis points. $Effective\ and\ realized\ spread$ are volume weighted and in basis points. $Constrained$ is the percent of the day where the spread is equal to one tick. $Depth\ at\ best$ is the dollar volume depth at the best prices. $Depth\ at\ X\ bps$ sums the depth at X bps on either side of the midpoint where X takes different values (see section 5.3). $Short-term\ volatility$ is the average 15-minute midpoint return volatility. $Effective\ spread$ \$500 and $\$200K$ estimates the effective spread in bps of a hypothetical trade of a dollar volume. The last two column reports the difference in means pre and post tick size increase and the p-value of the difference using a two-tailed t-test. ***, ** and * indicate the statistical significance at 1%, 5% and 10% levels respectively.

	Mean				Median			
Variable	Pre	Post	Difference	t-statistic	Pre	Post	Difference	t-statistic
$Order\ exposure\ (seconds)$	26.4	34.1	7.7	(7.94)***	18.6	22.9	4.2	(2.37)***
$Number\ of\ trades$	50.9	35.1	-15.7	(-25.20)***	47.5	28.7	-18.8	(-10.21)***
$Limit\ order\ /\ market\ order$	1.6	1.7	0.1	(5.48)***	1.6	1.6	0.0	(1.97)**
$Average\ market\ order\ volume$	18.7	21.4	2.6	(3.33)***	11.2	13.6	2.3	(6.46)***
$Average\ limit\ order\ volume$	10.3	11.4	1.0	(3.13)***	6.7	7.8	1.1	(6.44)***
$Average\ price\ difference\ (scaled)$	7.2	8.6	1.4	(7.82)***	5.5	6.9	1.4	(4.60)***
$Average\ price\ steps$	1.4	1.4	0.0	(-2.05)**	1.3	1.3	0.0	(-4.52)***
$Number\ of\ resting\ limit\ orders$	1.2	1.3	0.1	(12.12)***	1.2	1.3	0.1	(11.24)***
$Dollar\ volume\ (10{,}000\ USD)$	7.4	5.8	-1.6	(-10.23)***	5.6	4.1	-1.5	(2.31)***
$Quoted\ spread\ (bps)$	71.3	47.6	-23.7	(-31.71)***	63.9	43.7	-20.2	(-24.72)***
$Effective\ spread\ (bps)$	68.4	44.6	-23.8	(-28.17)***	60.5	39.7	-20.8	(-21.79)***
Realized spread (bps)	64.3	40.0	-24.3	(-28.38)***	57.1	36.3	-20.8	(-21.76)***
Price impact (bps)	4.1	4.6	0.4	(1.41)*	2.5	2.2	-0.3	(5.36)***
$Constrained\ (\%)$	5.3	8.2	3.0	(26.08)***	4.3	7.4	3.0	(16.17)***
$Depth\ at\ best\ (1{,}000\ USD)$	10.8	9.6	-1.2	(-5.43)***	8.8	8.0	-0.9	(-4.83)***
$Depth\ at\ X\ bps\ (1{,}000\ USD)$	106.3	142.5	36.3	(9.97)***	78.5	131.5	53.0	(50.70)***
$Short-term\ volatility$	3.7	2.6	-1.1	(-20.23)***	3.1	2.1	-1.0	(-16.60)***
$Effective\ spread\ \$500\ (bps)$	96.2	67.9	-28.3	(-30.54)***	87.3	64.2	-23.1	(-24.23)***

$Effective\ spread$ 200K$ (bps)	6,448.7	3,391.7	-3,057.0	(-15.42)***	4,279.6	2,117.0	-2,162.6	(-25.38)***

Table 4
Impact of relative tick size on trading behavior

This table reports the estimates of the two stage least squares regression: $Metric_{it} = \alpha_i + \beta_1 \$Volume_{it} + \beta_2 Trades_{it} + \beta_3 Volatility_{it} + \beta_4 MeanPrice_{it} + \beta_5 \widehat{RelativeTick}_{it} + \varepsilon_t$ where relative tick is the estimate of the first stage regression $Relative\ Tick_{it} = \alpha_i + \beta_1 \$Volume_{it} + \beta_2 Trades_{it} + \beta_3 Volatility_{it} + \beta_4 MeanPrice_{it} + \varepsilon_t$. $Relative\ Tick_{it}$ is the tick size in cents scaled by the price, multiplied by 10,000 and averaged within the 15-minute bucket. The control variables are $PercentChange_{it}$ which takes the value of zero before the tick size change and the value of the percent change in tick size after. $\$Volume_{it}$ measures the dollar volume in 10,000 USD traded for currency i in 15-minute interval t. $Trades_{it}$ is the number of trades. $Volatility_{it}$ is the currency-time high-low price range divided by the sum over two in basis points and $MeanPrice_{it}$ which is the average price in USD. In the second stage the dependent variables capture different measures of trading behavior for each currency and 15-minute interval in event time. There are fewer observations as not all 15-minute buckets had changes in the best prices. The *average market order volume* and *limit order volume* is the volume in units. The *average price steps* is how many price steps a market order goes through on average. The *number of resting limit orders* shows how many limit orders are resting at the same price step on average. Robust standard errors are reported in parentheses and clustered on currency pair. ***, ** and * indicate the statistical significance at 1%, 5% and 10% levels respectively. The trading behavior measures have fewer observations as not all 15-minute intervals observe trades. Resting limit orders per price steps exclude trades that only interact with one depth level and excludes the last limit orders on the last price step the market order interacted with to ensure that all price steps are filled.

Variable	$RelativeTick_{it}$	Limit order $volume_{it}$	Resting limit $orders_{it}$	Market order $volume_{it}$	Price $steps_{it}$
	(1)	(2)	(3)	(4)	(5)
$PercentChange_{it}$	2.14e-05***				
	(2.57e-06)				
$\widehat{RelativeTick}_{it}$		1.035***	0.0434***	1.756**	-0.0160***
		(0.325)	(0.00514)	(0.888)	(0.00488)
$\$Volume_{it}$	0.00220	0.144	0.00243***	0.362	0.00437***
	(0.00207)	(0.126)	(0.000735)	(0.328)	(0.00159)
$Trades_{it}$	-0.00198	-0.0326	0.000533***	-0.115	-0.00236***
	(0.00116)	(0.0251)	(0.000106)	(0.0772)	(0.000784)
$Volatility_{it}$	-0.00108	0.0119***	0.000119*	0.0564***	0.000741***
	(0.000815)	(0.00441)	(6.10e-05)	(0.0131)	(6.37e-05)
$Mean\ Price_{it}$	-0.000105	-0.000609	6.43e-05***	-0.00216	-3.37e-05
	(7.03e-05)	(0.000459)	(6.29e-06)	(0.00147)	(2.24e-05)
Observations	30,889	30,889	25,405	30,889	30,889
Adjusted R^2	0.469	0.004	0.023	0.009	0.044
Currency pair fixed effects	Yes	Yes	Yes	Yes	Yes
F-statistic	69.27				

Table 5
Impact of relative tick size increase on liquidity

This table reports the estimates of the two stage least squares regression: $Metric_{it} = \alpha_i + \beta_1 \$Volume_{it} + \beta_2 Trades_{it} + \beta_3 Volatility_{it} + \beta_4 MeanPrice_{it} + \beta_5 \widehat{RelativeTick}_{it} + \varepsilon_t$ where relative tick is the estimate of the first stage regression $Relative\ Tick_{it} = \alpha_i + \beta_1 \$Volume_{it} + \beta_2 Trades_{it} + \beta_3 Volatility_{it} + \beta_4 MeanPrice_{it} + \varepsilon_t$. The model has currency pair fixed effects. The control variables are $\$Volume_{it}$ which measures the dollar volume in 10,000 USD traded for currency i in 15-minute interval t. $Trades_{it}$ is the number of trades. $Volatility_{it}$ is the currency-time high-low price range divided by the sum over two in basis points. $MeanPrice_{it}$ is the average price in USD. The dependent variables $Metric_{it}$, are measures of liquidity for each currency and 15-minute interval in event time. $Quoted\ spread$ is time weighted and in basis points. $Effective\ and\ realized\ spread\ and\ price\ impact$ are volume weighted and in basis points. $Constrained$ is the percent of the day where the spread is equal to one tick. $Depth\ at\ best$ is the dollar volume depth at the best prices in 1,000 USD. $Depth\ at\ X\ bps$ sums the dollar volume depth at X bps on either side of the midpoint where X takes different values (see section 5.3) and is calculated in 1,000 USD. $Short-term\ volatility$ is the average 15-minute midpoint return volatility. $Effective\ spread\ \$500$ and $\$200K$ estimates the effective spread in bps of a hypothetical trade of a dollar volume. Robust standard errors are reported in parentheses and clustered on currency pair. ***, ** and * indicate the statistical significance at 1%, 5% and 10% levels respectively. The number of observations for effective and realized spread is lower as not all 15-minute intervals have trades and any trades with negative effective spreads due to sequencing error is excluded. Depth X has fewer observations as the exchange was offline for a few hours on August 25 and August 26.

Variable	*Quoted spread*$_{it}$	*Effective spread*$_{it}$	*Realized spread*$_{it}$	*Effective spread $500*	*Effective spread $200K*	*Depth at best*$_{it}$	*Depth at X bps*$_{it}$	*Short-term volatility*$_{it}$
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$\widehat{RelativeTick}_{it}$	-14.74***	-10.88***	-12.01***	-18.15***	-2,864***	-0.0582	16.85***	-0.235***
	(1.432)	(1.660)	(2.345)	(3.263)	(856.3)	(0.301)	(1.220)	(0.0454)
*$Volume*$_{it}$	0.164	0.166	0.181	0.0866	28.92	0.413***	1.597***	-0.0241*
	(0.184)	(0.199)	(0.210)	(0.182)	(21.91)	(0.0396)	(0.282)	(0.0144)
Trades$_{it}$	-0.289**	-0.321**	-0.338**	-0.325**	-22.75	0.0332	-0.293***	0.0133*
	(0.144)	(0.144)	(0.150)	(0.161)	(13.90)	(0.0206)	(0.103)	(0.00765)
Volatility$_{it}$	0.212***	0.374***	0.342***	0.277***	3.439	-0.0179**	-0.172***	0.0243***
	(0.0301)	(0.0267)	(0.0315)	(0.0381)	(4.954)	(0.00781)	(0.0635)	(0.000861)
Mean Price$_{it}$	-0.00641	-0.00527	-0.00500	-0.00708	-1.725***	0.00532***	0.0206***	0.000319
	(0.00400)	(0.00374)	(0.00385)	(0.00472)	(0.495)	(0.000925)	(0.00277)	(0.000216)
Observations	33,696	30,449	30,449	33,696	33,696	33,696	33,011	33,696
Adjusted R^2	0.205	0.324	0.252	0.198	0.007	0.079	0.007	0.474
Currency pair fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table 6
Large versus small relative tick regression

This table shows the coefficient and t-statistic on the post dummy or $\widehat{RelativeTick}_{it}$ variable. Model (1) presents the results from the second stage regression shown in Table 8. Model (2) estimates the effect for the currency pair which after the change has a larger relative tick size, specifically ETC-BTC. Model (3) considers the currency pair which after the tick size change have a smaller relative tick size, specifically BTC-USD. Model (1) has currency pair fixed effects and clustered standard errors. Model (2) and (3) have robust standard errors clustered on datetime. The dependent variables are measures of market quality for each currency and 15-minute interval in event time. $Quoted\ spread$ is time weighted and in basis points. $Effective\ and\ realized\ spread\ and\ price\ impact$ are volume weighted and in basis points. $Constrained$ is the percent of the day where the spread is equal to one tick. $Depth\ at\ best$ is the dollar volume depth at the best prices in 1,000 USD. $Depth\ at\ X\ bps$ sums the dollar volume depth at X bps on either side of the midpoint where X takes different values (see section 1.3) and is calculated in 1,000 USD. $Short-term\ volatility$ is the average 15-minute midpoint return volatility. $Effective\ spread$ \$500 and \$200K estimates the effective spread in bps of a hypothetical trade of a dollar volume. Robust standard errors are reported in parentheses. ***, ** and * indicate the statistical significance at 1%, 5% and 10% levels respectively.

	2SLS	Large relative tick	Small relative tick
	(1)	(2)	(3)
$Quoted\ spread\ (bps)$	-14.74***	-15.56***	-9.84***
	(1.432)	(0.700)	(1.128)
$Effective\ spread\ (bps)$	-10.88***	-13.47***	-7.15***
	(1.660)	(0.844)	(1.436)
Realized spread (bps)	-12.01***	-13.00***	-11.63***
	(2.345)	(0.897)	(1.676)
$Depth\ at\ best$ (1,000 USD)	-0.0582	-0.236**	2.182
	(0.301)	(0.0994)	(3.011)
$Depth\ at\ X\ bps$ (1,000 USD)	16.85***	9.054*	63.28***
	(1.220)	(4.922)	(19.72)
$Short-term\ volatility$	-0.235***	-0.0722*	-0.9940***
	(0.0454)	(0.0373)	(0.118)
$Effective\ spread$ \$500 (bps)	-18.15***	-16.17***	-11.53***
	(3.263)	(0.741)	(1.158)
$Effective\ spread$ \$200K (bps)	-2,864***	-773.8***	4,565
	(856.3)	(49.24)	(4,731)

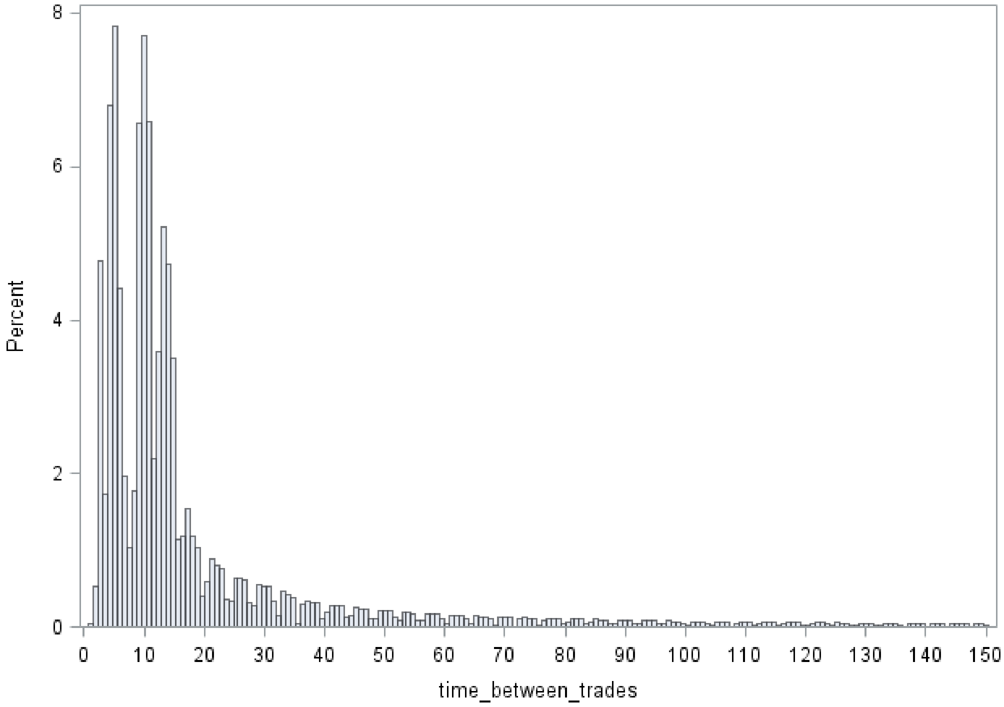
Appendix A1: Trade aggregation

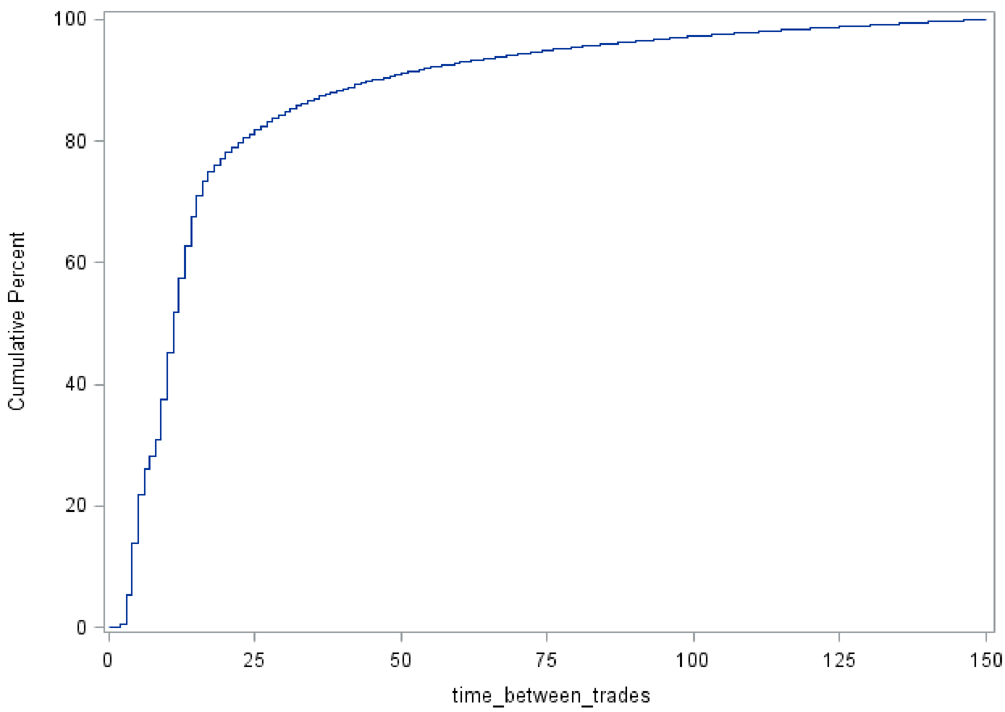
To calculate high frequency liquidity metrics, we need to identify the total size and price of each trade executed in the book. As with trade and quote data from traditional data sources, each observation constitutes a limit order executed against one or part of a larger market order. To calculate the entire trade size and average price, we therefore have to aggregate these limit orders to one market order. However, due to the relatively slow matching engine on Kraken, the time stamps of each limit order within one market order are rarely identical. To aggregate the trades correctly we calculate the milliseconds between each limit order and plot a histogram and cumulative distribution function shown in Appendix Figure 1. The graphs show that 80% of the trades occur within 20 milliseconds of each other indicating that the matching engine delays consecutive interactions of market orders with limit orders by up to 20 milliseconds. We therefore aggregate limit orders which occur within 20 milliseconds of each other in the same trade direction, buy or sell, as part of one market order. The market order is then assigned a total trade volume and a volume weighted average price.

Appendix Figure 1

Histogram and cumulative distribution function of time between trades

The graphs show the distribution and cumulative distribution of the time between trades in milliseconds for all six currencies on Kraken between August 1, 2017 and October 21, 2017. For the purposes of this graph observations greater than 0.15 seconds have been omitted to clearly show the skewed distribution.





Appendix A2: Realized spread lead time estimation

When calculating which midpoint to compare the price of a trade to when calculating the realized spread it is important to use the correct lead time. If the lead time is too short, the inventory effect will be included and the price impact will be overstated. If the lead time is too long other trades may have occurred and the price impact will therefore include responses by other information which will give a biased estimate. To estimate the correct lead time a vector auto regression is estimated following the structural form shown in Eq. (a) and (b).

$$x_t = \mu^x + \sum_{i=1}^{180} \phi_i^r r_{t-i} + \sum_{i=1}^{180} \phi_i^x x_{t-i} + \varepsilon_t^x \quad \text{(a)}$$

$$r_t = \mu^r + \sum_{i=1}^{180} \phi_i^r r_{t-i} + \sum_{i=0}^{180} \phi_i^x x_{t-i} + \varepsilon_t^r \quad \text{(b)}$$

where individual currency pair and date subscripts are suppressed, t is one second intervals, x_t is signed dollar volume of trades in the one second interval t, r_t is the log midpoint change in the t^{th} interval, ε_t^x is unanticipated signed dollar volume and ε_t^r is a midpoint innovation that is not caused by order flow. All variables are converted to USD using the daily trade price on Gemini so the shock is of equal size. Gemini is used as it is the only exchange for which we have all USD denominated exchange rates. Each Eq. contains 180 lags of signed dollar volume and midpoint changes.

A reduced form VAR is estimated following Eq. (c) and (d).

$$x_t = \mu^x + \sum_{i=1}^{180} \alpha_i^r r_{t-i} + \sum_{i=1}^{180} \alpha_i^x x_{t-i} + e_t^x \quad \text{(c)}$$

$$r_t = \mu^r + \sum_{i=1}^{180} \beta_i^r r_{t-i} + \sum_{i=1}^{180} \beta_i^x x_{t-i} + e_t^r \quad \text{(d)}$$

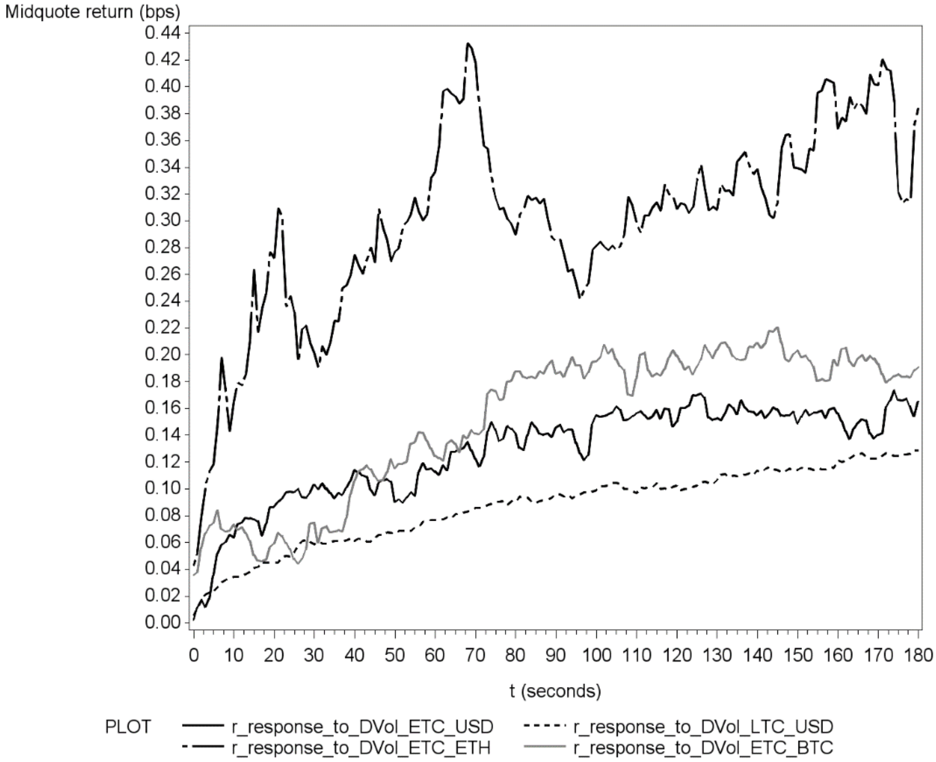
where $e_t^x = \varepsilon_t^x$ and $e_t^r = b_1 e_t^x + \varepsilon_t^r$. The error terms are serially uncorrelated and i.i.d. and contemporaneously correlated across equations.

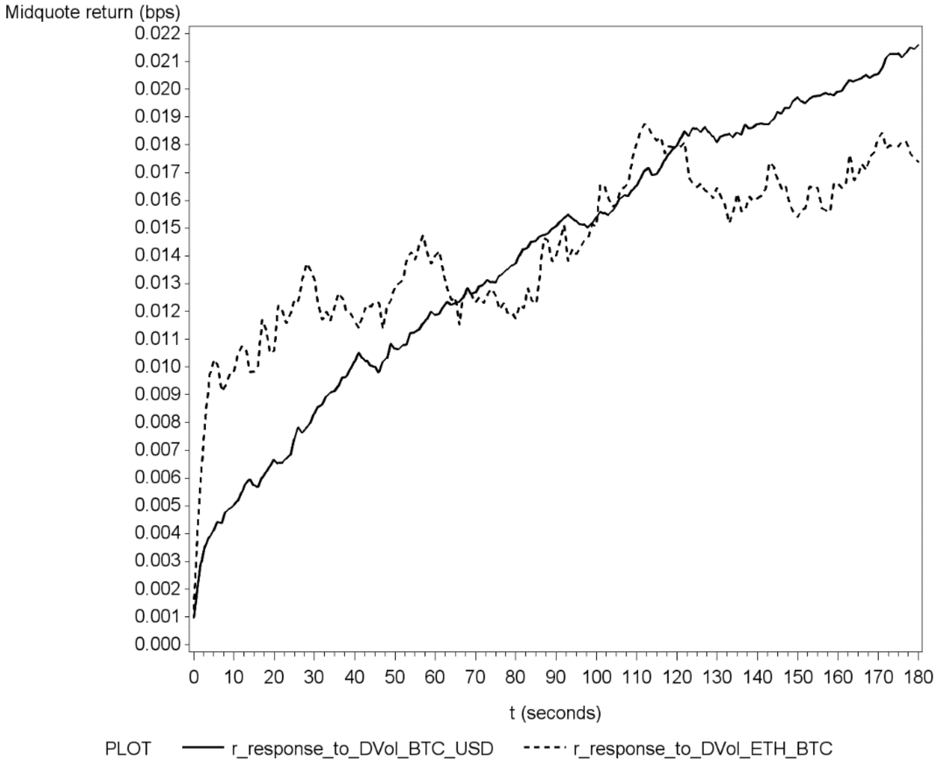
To identify how long it takes for the price impact to converge, a shock to e_0^x is introduced representing a 200-dollar volume buyer-initiated trade. The impulse response functions are then graphed to observe when the price converges. Appendix Figure 2 shows that most currency pairs converge after 10-20 seconds. Its looks as though the USD denominated currency pairs take longer to converge than the cryptocurrency cross rates. When introducing a 200-dollar seller-initiated trade as a shock the same results are produced. Based on these results the price of a trade will be compared to the midpoint 10 seconds after for ETC-BTC, ETC-ETH and ETH-BTC and 20 seconds after for LTC-USD, ETC-USD and BTC-USD.

Appendix figure 2

Response functions of a 200 USD buyer-initiated trade on the midpoint return

The figure shows the response functions of all currency pairs in the sample for the period 23rd August to 13th September 2017. Midpoints and dollar volumes are converted to USD using the daily traded price on Gemini. Gemini is used as it is the only exchange for which we have all USD denominated exchange rates.





Appendix A3: Continued summary tables

Table A1

Summary statistics of trading behavior and liquidity continued

The table shows summary statistics of trading behavior, liquidity and control variables for ETH-BTC and LTC-USD over the period 1st August to 5th October 2017 on Kraken. All metrics are daily averages. $Order\ exposure$ is the number of seconds the best bid or ask order is exposed. $Limit\ order\ /\ market\ order$ shows the proportion of limit orders to market orders. The $average\ market\ order\ and\ limit\ order\ volume$ shows the volume in ETH or LTC. The $average\ price\ difference$ is the difference between limit order prices within a market order scaled by 100. The $average\ price\ steps$ is how many price steps a market order goes through on average. The $number\ of\ resting\ limit\ orders$ shows how many limit orders are resting at the same price step on average. $Quoted\ spread$ is time weighted and in basis points. $Effective\ and\ realized\ spread\ and\ price\ impact$ are volume weighted and in basis points. $Constrained$ is the percent of the day where the spread is equal to one tick. $Quoted\ spread\ (ticks)$ shows the pre and post change quoted spread in number of ticks time weighted. $Depth\ at\ best$ and $depth\ at\ X\ bps$ sums the USD depth at X bps on either side of the midpoint where X takes the value of 22 basis points for ETH-BTC and 39 basis points for LTC-USD. $Short-term\ volatility$ is the average 15-minute midpoint return volatility. $Effective\ spread$ \$500 and \$200K estimates the effective spread in bps of a hypothetical trade of a dollar volume. The $number\ of\ trades$ is the daily total. $Dollar\ volume$ is the daily total displayed in 10,000 USD. $Volatility$ is the currency-time high-low price range divided by the sum over two in basis points. The $mean\ price$ shows the average price in USD. The $relative\ tick$ is the tick size in cents over the price and averaged in the 15-minute buckets.

	ETH-BTC					LTC-USD				
	Mean	Median	Std	Minimum	Maximum	Mean	Median	Std	Minimum	Maximum
Panel 1: Trading behavior metrics										
$Bid\ order\ exposure\ (seconds)$	13.60	12.39	8.00	6.75	71.12	22.23	18.10	13.07	7.81	86.92
$Limit\ order\ /\ market\ order$	1.62	1.61	0.14	1.28	1.91	1.71	1.72	0.11	1.48	2.07
$Average\ market\ order\ volume$	3.93	3.57	1.66	1.51	11.63	12.87	12.58	3.99	5.60	21.34
$Average\ limit\ order\ volume$	2.01	1.79	0.79	0.92	6.02	6.97	6.79	2.01	2.76	11.71
$Average\ price\ difference\ (scaled)$	0.00	0.00	0.00	0.00	0.00	1.81	1.54	0.96	0.67	5.02
$Average\ price\ steps$	1.33	1.33	0.08	1.12	1.49	1.51	1.51	0.10	1.36	1.81
$Number\ of\ resting\ limit\ orders$	1.28	1.27	0.08	1.14	1.57	1.15	1.15	0.07	1.05	1.44
Panel 2: Liquidity metrics										
$Quoted\ spread\ (bps)$	14.61	13.79	4.85	8.22	40.44	35.51	34.53	16.96	15.02	127.15
$Effective\ spread\ (bps)$	25.79	22.83	9.68	13.00	59.07	45.41	43.67	18.30	21.96	126.11
Realized spread (bps)	24.51	21.25	9.82	9.45	57.04	40.44	37.56	16.21	19.89	113.43
$Price\ impact\ (bps)$	1.27	0.67	1.86	-1.09	7.24	4.97	3.67	5.24	-1.62	27.80
$Constrained$ (%)	13.81	13.41	4.33	3.51	23.99	7.87	6.70	5.37	0.88	27.10
$Quoted\ spread\ (pre\ ticks)$	132.55	125.78	40.70	91.09	289.06	21,203.24	20,676.04	8,257.48	12,206.52	57,391.67
$Quoted\ spread\ (post\ ticks)$	8.28	7.88	1.40	5.65	11.27	14.50	12.43	6.20	7.92	32.12
$Depth\ at\ best\ (1{,}000\ USD)$	21.05	20.15	5.49	13.24	48.42	53.28	51.27	18.68	29.28	147.02
$Depth\ at\ X\ bps\ (1{,}000\ USD)$	497.01	437.71	293.60	130.59	1631.36	3551.08	3,049.65	2104.71	682.12	9,087.48
$Short-term\ volatility$	13.90	11.39	9.62	3.33	71.69	6.62	5.64	3.55	2.24	19.18
$Effective\ spread\ \$500\ (bps)$	144.19	117.23	67.16	43.72	394.29	75.41	74.81	45.86	25.49	346.55
$Effective\ spread\ \$200K\ (bps)$	2.32	2.01	1.13	0.94	6.82	3.24	2.78	1.59	1.28	9.46
Panel 3: Control variables										
$Number\ of\ trades$	6,954.68	6,910.00	3,436.30	1,772.00	16,662.00	3,601.20	3,056.50	2,005.40	939.00	9,033.00
$Dollar\ volume\ (10{,}000\ USD)$	925.24	664.15	718.87	177.87	4,101.43	302.65	200.43	251.06	61.97	1,147.54
$Volatility\ (bps)$	70.64	61.96	33.81	29.34	175.56	98.24	86.42	56.16	33.59	339.58
$Mean\ price$	297.13	295.54	37.13	215.05	394.12	54.93	51.59	11.14	42.38	81.69
$Relative\ tick\ (bps)$	0.70	0.14	0.64	0.11	1.48	0.81	0.01	0.91	0.00	2.13

Table A2

Summary statistics of trading behavior and liquidity continued

The table shows summary statistics of trading behavior, liquidity and control variables for ETC-ETH and ETC-BTC over the period 1st August to 5th October 2017 on Kraken. All metrics are daily averages. $Order\ exposure$ is the number of seconds the best bid or ask order is exposed. $Limit\ order\ /\ market\ order$ shows the proportion of limit orders to market orders. The $average\ market\ order\ and\ limit\ order\ volume$ shows the volume in ETC. The $average\ price\ difference$ is the difference between limit order prices within a market order scaled by 100. The $average\ price\ steps$ is how many price steps a market order goes through on average. The $number\ of\ resting\ limit\ orders$ shows how many limit orders are resting at the same price step on average. $Quoted\ spread$ is time weighted and in basis points. $Effective\ and\ realized\ spread\ and\ price\ impact$ are volume weighted and in basis points. $Constrained$ is the percent of the day where the spread is equal to one tick. $Quoted\ spread\ (ticks)$ shows the pre and post change quoted spread in number of ticks time weighted. $Depth\ at\ best$ and $depth\ at\ X\ bps$ sums the USD depth at X bps on either side of the midpoint where X takes the value of 101 basis points for ETC-ETH and 99 basis points for ETC-BTC. $Short-term\ volatility$ is the average 15-minute midpoint return volatility. $Effective\ spread$ \$500 and \$200K estimates the effective spread in bps of a hypothetical trade of a dollar volume. The $number\ of\ trades$ is the daily total. $Dollar\ volume$ is the daily total displayed in 10,000 USD. $Volatility$ is the currency-time high-low price range divided by the sum over two in basis points. The $mean\ price$ shows the average price in USD. The $relative\ tick$ is the tick size in cents over the price and averaged in the 15-minute buckets.

	ETC-ETH					ETC-BTC				
	Mean	Median	Std	Minimum	Maximum	Mean	Median	Std	Minimum	Maximum
Panel 1: Trading behavior metrics										
$Bid\ order\ exposure\ (seconds)$	40.99	35.45	20.52	13.80	111.21	57.22	52.56	27.74	14.97	125.76
$Limit\ order\ /\ market\ order$	1.51	1.52	0.15	1.12	1.94	1.48	1.47	0.12	1.20	1.78
$Average\ market\ order\ volume$	29.54	27.15	14.24	5.73	66.12	46.11	44.21	18.07	8.03	87.89
$Average\ limit\ order\ volume$	16.99	16.42	7.55	3.15	34.49	26.29	25.46	10.28	4.44	56.43
$Average\ price\ difference\ (scaled)$	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
$Average\ price\ steps$	1.36	1.36	0.13	1.08	1.74	1.25	1.24	0.08	1.09	1.46
$Number\ of\ resting\ limit\ orders$	1.14	1.12	0.09	1.00	1.47	1.26	1.25	0.11	1.10	1.71
Panel 2: Liquidity metrics										
$Quoted\ spread\ (bps)$	128.48	112.51	52.58	58.32	285.95	96.96	84.11	42.72	45.72	324.18
$Effective\ spread\ (bps)$	117.40	97.95	52.86	47.99	266.92	95.60	88.27	43.49	43.71	298.88
Realized spread (bps)	111.58	94.30	51.88	46.81	251.69	90.51	83.57	41.76	40.61	274.80
$Price\ impact\ (bps)$	5.82	4.60	6.29	-4.47	27.27	5.09	4.61	4.33	-2.71	24.08
$Constrained$ (%)	2.23	0.99	2.53	0.00	10.31	5.37	5.01	2.86	1.27	14.64
$Quoted\ spread\ (pre\ ticks)$	71,999.43	69,730.17	23,372.94	31,165.26	122,019.52	4,865.45	4,482.61	1,472.37	3,077.64	10,633.13
$Quoted\ spread\ (post\ ticks)$	44.46	39.15	15.94	21.67	76.46	22.84	20.72	7.65	12.67	39.60
$Depth\ at\ best\ (1{,}000\ USD)$	169.72	147.49	70.34	77.75	360.17	120.97	106.47	48.10	65.57	354.22
$Depth\ at\ X\ bps\ (1{,}000\ USD)$	8,404.13	5,083.96	10,456.10	985.58	57,812.67	2,600.55	1,773.64	2,147.57	615.34	13,546.07
$Short-term\ volatility$	6.92	6.48	3.01	1.43	14.87	9.76	9.62	3.41	4.57	19.75
$Effective\ spread$ \$500 (bps)	139.88	128.87	96.17	27.93	609.89	130.82	123.31	62.82	41.14	447.38
$Effective\ spread$ \$200K (bps)	3.95	2.84	2.84	1.27	11.98	4.26	3.27	2.73	1.49	14.88
Panel 3: Control variables										
$Number\ of\ trades$	795.50	509.00	692.63	80.00	3,007.00	1,291.68	968.50	1,130.60	239.00	4,882.00
$Dollar\ volume\ (10{,}000\ USD)$	33.99	20.99	42.88	1.17	290.54	78.59	51.80	76.80	7.87	467.63
$Volatility\ (bps)$	65.91	45.40	59.64	5.22	225.42	86.36	71.72	58.05	14.97	263.90
$Mean\ price$	14.27	14.30	2.32	10.17	20.55	14.27	14.21	2.33	10.15	20.52
$Relative\ tick\ (bps)$	1.05	0.18	1.13	0.00	2.71	1.72	2.47	1.55	0.02	3.61