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Locked and crossed markets on NASDAQ and the NYSE ☆

Andriy V. Shkilko[a,*], Bonnie F. Van Ness[b], Robert A. Van Ness[b]

[a]*School of Business and Economics, Wilfrid Laurier University, Waterloo, ON N2L 3C5, Canada*
[b]*School of Business Administration, University of Mississippi, University, MS 38677, USA*

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Abstract

The NBBO for an average active stock is non-positive (locked or crossed) 10.58% and 4.05% of the time on, respectively, the NASDAQ and the NYSE inter-markets. Locks and crosses are frequent fleeting events that usually accompany significant price changes. Non-positive NBBOs arise because of (i) simultaneous and (ii) tardy quote updates, (iii) electronically unreachable quotes, (iv) reluctance to trade against autoquotes, (v) order transit considerations, and (vi) ECN liquidity attraction efforts. Most locks and crosses result from competitive trading practices in contemporary fragmented markets.

1. Introduction

The National Best Bid and Offer (NBBO) for a frequently traded NASDAQ stock is locked or crossed 10.58% of the time (about 41 minutes cumulatively every day), whereas the NBBO for an active NYSE stock is locked or crossed 4.05% of the time. In the NASDAQ inter-market, 15.37% of quotes are affected by non-positive inside spreads, with a similar statistic in the NYSE inter-market being 4.27%. Further, 22.17% of trades

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*Corresponding author. Tel.: +1 6628011361; fax: +1 6629157968.
E-mail address: ashkilko@bus.olemiss.edu (A.V. Shkilko).

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in the NASDAQ sub-sample and 5.79% of trades in the NYSE sub-sample are executed during locked and crossed NBBOs. Locks and crosses are frequent fleeting events: they occur about every minute in the sample NASDAQ stocks (about every 9 min in the sample NYSE stocks) and terminate quickly. A lock (cross) on NASDAQ is usually resolved within 5 (10) s, whereas a lock (cross) on the NYSE is resolved within 7 (28) s. The table below contains a brief summary of our findings.

Locked (crossed) markets	NASDAQ	NYSE
Occur, % of the time	10.58	4.05
Affect, % of quotes	15.37	4.27
Affect, % of trades	22.17	5.79
Occur every, seconds	68.76	532.15
Last for, seconds	4.83 (9.93)	7.31 (27.96)

The market in a stock is considered to be locked (crossed) when the inside ask is equal to (is less than) the inside bid, making the NBBO spread equal to (less than) zero. Non-positive spreads usually arise as a result of interaction of NBBO quotes posted by two or more trading venues. Although one venue's NBBO-forming ask quote is normally higher than this venue's bid quote (Fig. 1), this ask quote may be equal to (or even less than) an NBBO-forming bid quote posted by a different venue. Fig. 1 shows that locked and crossed markets do not directly interfere with the market makers' abilities to cover their expenses: even if the NBBO is non-positive, involved venues are still able to collect spread revenues.

We assert that extant academic literature lacks empirical evidence on non-positive spread episodes that occur during the trading day. This study attempts to improve the profession's understanding of trading mechanisms by providing a thorough examination of locked and crossed NBBOs and by identifying several reasons for their origination. In addition, we challenge the conventional perception of non-positive spreads as detrimental occurrences, as we do not find sufficient evidence of market quality deterioration. We view non-positive spreads as a natural mechanism that allows market participants to cope with today's increasingly competitive and fragmented trading environment.

We are aware of only a few studies that analyze instances of non-positive spreads. Cao et al. (2000) find that informed NASDAQ dealers use locks and crosses during pre-opening sessions to show their less informed colleagues the direction in which prices are moving. In their sample of the 50 most active NASDAQ-listed stocks, inside quotes are crossed 24% of the time and locked 11% of the time during the pre-opening, while the market is locked and crossed only 0.3% of the time during the regular trading hours. Battalio et al. (2004) document instances of non-positive spreads in the exchange-listed options markets. They find that the amount of time actively traded options spend in locked and crossed markets decreases following the imposition of more stringent quoting and disclosure rules on options trading.

A number of empirical studies treat non-positive spread events as insignificant and filter them out of samples. For instance, Bessembinder (2003) investigates inter-market competition on the NYSE and eliminates 3.12% of the sample trades, because they are completed while the NBBO spread is non-positive. In our sample, transactions eliminated

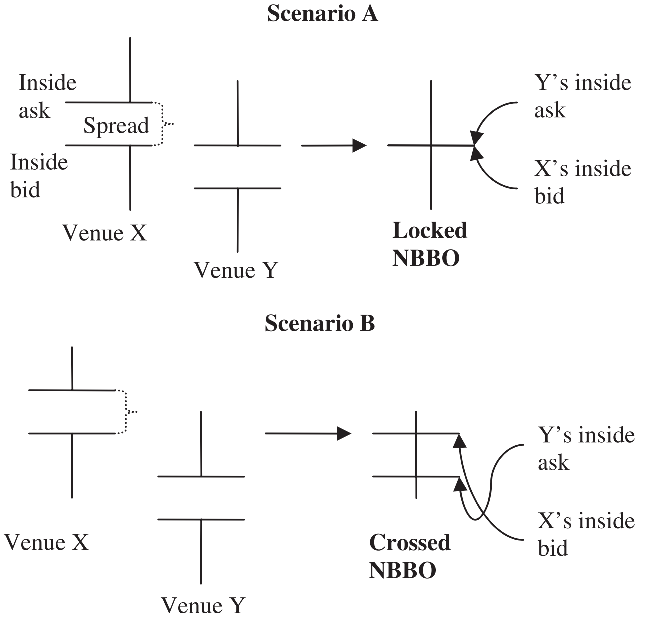

Fig. 1. Composition of locked and crossed NBBOs. In Scenario A, Venue X's inside bid is equal to Venue B's inside ask, leading to a locked NBBO. In Scenario B, Venue X's inside bid is greater than Venue B's inside ask, leading to a crossed NBBO. Note that although the inter-market is locked or crossed, market makers on both venues are still collecting spread revenues.

in this fashion would comprise 5.79% of the NYSE and 22.17% of the NASDAQ inter-market trades, limiting the sample. Although the number of locked and crossed markets is alarming, several recent papers (e.g., Boehmer, 2005; Lipson, 2004; Werner, 2003) that examine execution quality in a competitive market setting refrain from addressing this issue.[1]

The SEC's recent Regulation NMS recommends that market participants avoid initiating non-positive spreads, because locks and crosses are "inconsistent with fair and orderly markets and detract [...] from market efficiency."[2] The commission also blames zero and negative spreads for creating confusion for investors as it becomes "unclear what is the true trading interest in the stock."[3] We suggest that although non-positive NBBOs may seem unnatural, they represent the traders' adjustment to the high level of fragmentation in contemporary markets. We show that locked and crossed NBBOs are caused by (i) simultaneous and (ii) tardy quote updates, (iii) electronically unreachable quotes, (iv) reluctance to trade against autoquotes, (v) order transit considerations, and (vi) ECN liquidity attraction efforts.

[1]Boehmer (2005) and Lipson (2004) use the Dash-5 data that do not incorporate all transactions that occur when the market is crossed. Under the 11Ac1-5 rule, executions are exempt from reporting when the market is crossed for more than 30 seconds.

[2]U.S. Securities and Exchange Commission (2005), Regulation NMS, p.194.

[3]Ibid.

2. Causes of non-positive NBBOs

There are several factors most often blamed for causing non-positive spreads. The first one is faulty connectivity among market centers. Since both the NYSE and NASDAQ have multiple venues quoting their securities, improper coordination while posting quotations may lock or cross the market. The point is asserted by Sang Lee, a manager of the securities and investments group at Celent Communications who claims that "the problem is [...] multiple venues for trading NASDAQ stocks."[4] Indeed, the multiplicity of quote and trade sources may become a serious impediment to efficient market operations. Suppose two venues post quotes simultaneously or within a very short time period. If one of them unintentionally posts a bid that is equal to (higher than) the offer of the other, the inter-market locks (crosses). In a similar fashion, if market makers on one venue are not aware of the quotes posted by the other venue because these quotes are electronically unreachable, the NBBOs may be unintentionally locked or crossed.[5] Our findings support this notion to a large degree. We show that, in the inter-market setting, non-positive spreads that result from simultaneous posting of locking (crossing) quotes are rather frequent and comprise 11.46% and 20.16% (8.74% and 31.81%) of lock (cross) initiations on, respectively, the NYSE and NASDAQ inter-markets.

As shown by Cao et al. (2000), better informed NASDAQ dealers lock and cross inside quotes during the pre-opening session to signal the direction and magnitude of price movements. The authors suggest that, in the absence of trading, non-positive spreads are an effective method of price discovery. Our analysis does not concentrate on the pre-opening session, but rather on the trading day, during which price movements can be observed by all participants, and better informed market makers may profitably trade against outdated quotes instead of locking or crossing them. We hypothesize, however, that in certain cases, trading against stale quotes may not be plausible from an active market participant's standpoint. For instance, if (i) an outdated quote is posted by a slower or a non-responsive market on which execution may take an unreasonably long period of time, or if (ii) the quote is an auto-quote for only one hundred shares, the trader who is seeking a speedy and certain execution may choose to lock (cross) such a quote, instead of trying to execute against it.

Our findings are, generally, in line with this view. Regression results show that, on AMEX and Chicago for NASDAQ stocks and on Boston, National, Chicago, and Philadelphia for the NYSE stocks, the quote's time outstanding increases the probability of a lock (cross). For the rest of the venues, however, time outstanding either has no effect, or prevents non-positive spreads from arising. Apparently, market participants often find it problematic to trade against the outdated quotes posted by the markets listed above, whereas the rest of the venues are more responsive and therefore avoid having their outdated quotes locked and crossed.[6] In addition, we show that, in the NASDAQ inter-

[4]Schmerken (2003). "NASDAQ's battle over locked and crossed markets." Wall Street and Technology, May, 12–18.

[5]At the time of our study, connectivity between AMEX and SuperMontage had certain flaws. Often, AMEX quotes were electronically unreachable, so the SuperMontage participants frequently ignored them, causing locks and crosses.

[6]At the time of our study, trades on Chicago may execute though market makers, floor brokers, and an automated execution system MAX®. According to the venue's web site, "most of the retail trading activity takes place electronically through MAX®," which may cast doubts on our argument of the venue being slow. We

market, autoquotes are locked and crossed rather frequently, respectively in 22.78% and 26.14% of cases, especially when compared to their overall involvement in formation of only 16.75% of the NBBOs. In the NYSE sub-sample, autoquotes are locked and crossed relatively seldom, in less than 0.5% of cases, most likely due to the fact that, in the NYSE inter-market, 100-share NBBO quotes are not considered economic, and traders are entitled to ignore them.

Multi-market trading may, at times, lead to complications for investors concerned with the timeliness of executions. Suppose venue A is currently quoting the best bid, and there is a sizeable number of market sell orders aligned to be executed against this bid. Suppose further that venue B does not quote the best bid, but there is a trader on this venue who wishes to sell at the current NBBO bid. One way for this trader to transact is to communicate his order to venue A. Alternatively, the trader may post a locking offer (submit a marketable sell limit order) on (to) market B. At times of significant price changes, the trader may be reluctant to use the former alternative, because while the order is in transit, the quote on the receiving venue may change. From the trader's standpoint, a more attractive approach is to ignore the other market's quote and alter his own quotes, creating a lock.

We test the order-in-transit argument using several instruments correlated with the probability of a rapid quote change on the lockee. In particular, we control for the price change in the preceding 3 min, lockee's lagged BBO width, and the preceding 3 min volume on the lockee. We expect rapidly changing prices, narrow BBOs, and high volume on the locked venues to contribute to traders' fears of untimely executions and to increase the probability of a lock or a cross. Regression results generally support our logic.

ECNs do not employ professional market makers and are therefore subject to liquidity shortages. To prevent such shortages, ECNs try to attract liquidity-providing limit orders by partially refunding the access fees (e.g., Hansch, 2007; Hasbrouck and Saar, 2005). Limit orders submitted to most of the ECNs and, sometimes, NASDAQ are typically rewarded with a 1 to 2 mils (millicents) per share rebate of a standard 3-mil non-subscriber access fee, while liquidity-consuming market orders are charged the entire fee. To receive these rebates, ECNs and NASDAQ clients who wish to trade at an outstanding market price often submit marketable limit orders with a desired sell (buy) price equal to that of the NBBO bid (ask). Upon posting, these sell (buy) orders lower the offer (raise the bid) and lock the NBBO. Certain ECNs (e.g., Island) go even further in their quest for liquidity and do not accept market orders. If a trader on Island is looking to buy (sell) at an outstanding NBBO price and wishes to execute in a timely manner, she has to submit a marketable limit order with the limit price equal to the NBBO ask (bid) and, consequently, lock the market.[7]

(*footnote continued*)
suggest that despite the technological advances, Chicago's electronic system may still largely depend on the market makers' quotes. Since these quotes are integrated into the MAX® system, if the specialist is slow with an update, the entire system may carry a "stale" quote, which may lead to a locked or a crossed market.

[7]ECN rebates are not expected to cause negative NBBOs, due to the fact that the reward for submitting marketable limit orders is less than one cent per share. By crossing the NBBO, a trader forgoes at least one cent of revenue, as she could have sold (bought) for more (less) if she had chosen to submit a market order or a locking marketable limit order. Since the access fees are lower than one cent per share, crossing the market for the sake of rebates is an unprofitable strategy.

We show that ECNs frequently initiate zero spreads and are often the ones to unlock the market after volume sufficient to deplete the locking quote has been executed. The latter finding may be attributed to the fact that quotes produced by the marketable limit orders are withdrawn after these orders are executed. Lastly, the outcome of Tobit regressions on Dash-5 data indicates that a marketable limit order is the only order type that consistently positively influences the number of zero spreads initiated by the ECNs.

3. Sample

The sample consists of quoting and trading data for the 100 most actively traded NYSE- and the 100 most actively traded NASDAQ stocks in October–December 2003.[8] The data are obtained from the TAQ database. For the NASDAQ sub-sample, we use data for the entire trading day, from 9:30 a.m. to 4:00 p.m., while for the NYSE-listed securities, the first fifteen minutes of trading on each day are omitted to exclude the effects of an opening call. Quantities of market and various types of limit orders submitted to the ECNs are obtained from Transaction Auditing Group, Inc. and Instinet Group, Inc.

During the sample period, trading and quoting in NASDAQ stocks occur on six market centers: the American Stock Exchange (AMEX), the National Stock Exchange, the NASD Alternative Display Facility (ADF), the Chicago Stock Exchange, the Pacific Stock Exchange, and NASDAQ SuperMontage.[9] In the past several years, an increase in competition for order flow in NASDAQ securities made the TAQ data more informative about the inter-market structural landscape and allowed for sufficiently accurate identification of the leading competitors. Goldstein et al. (2007) mention that, from mid-April 2003 until February 2004, the three ECNs – Island, Instinet, and ArcaEx – dominate on, respectively, the National Stock Exchange, the ADF, and the Pacific Stock Exchange. Since the time interval chosen for this study falls into the aforementioned period, we treat the data from National, ADF, and Pacific as generated by, respectively, Island, Instinet, and ArcaEx for the NASDAQ sub-sample.[10]

The NYSE-listed stocks are traded and quoted by seven market centers: the Boston Stock Exchange, the National Stock Exchange, the Chicago Stock Exchange, the New York Stock Exchange (NYSE), the Pacific Stock Exchange, NASDAQ SuperMontage, and the Philadelphia Stock Exchange. Goldstein, Shkilko, Van Ness, and Van Ness (2006) claim that ECNs are not as active in the NYSE inter-market as they are in the market for the NASDAQ stocks, and that the networks' activity cannot be adequately distinguished from that of the hosting market venues. For this reason, we do not identify the ECNs for the NYSE sub-sample.

Table 1 provides sample summary statistics, with results for the NASDAQ sub-sample presented in Panel A. Our findings indicate that quoting and trading differ dramatically among venues. ArcaEx appears to be the most active in terms of quoting and posts 42.42% of the inter-market quotes, whereas two other ECNs participate in quoting relatively less

[8] We define the most actively traded stocks as the ones with the highest trading volume.

[9] The Cincinnati Stock Exchange changed its name to the National Stock Exchange on November 7, 2003. We choose to refer to the venue with its newly acquired name.

[10] During our sample period, Instinet reports through both ADF and SuperMontage. In addition, a number of smaller ECNs such as Attain, Brut, Bloomberg Tradebook, etc. report through SuperMontage. As TAQ data do not allow us to distinguish between these networks and NASDAQ dealers, we are particularly cautious when explaining the results obtained for the venue.

Table 1
Summary statistics

The table contains summary statistics on quoting and trading of venues that make market in 100 most active NASDAQ and 100 most active NYSE-listed stocks. Panel A contains results for the NASDAQ sub-sample, while Panel B describes the NYSE sub-sample. Market shares represent numbers of quotes/trades executed by the individual venues as a percentage of the total number of quotes/trades executed in the corresponding inter-market. For several markets, the number of stocks quoted and/or traded is given as a range, in which the lower bound represents the number of stocks quoted/traded on the day with the lowest quoting/trading activity, and the higher number presents a similar statistic for the day with the highest activity. Differences across venues are statistically significant, with the exception of the difference in trade sizes for pairs AMEX-Chicago and National-ADF in the NASDAQ sub-sample; as well as difference in trade market shares for Chicago-Pacific and trade sizes for Boston-National in the NYSE sub-sample.

	NYSE	NASDAQ	Pacific (ArcaEx)	National (Island)	ADF (Instinet)	Chicago	AMEX	Boston	Philadelphia
Panel A: NASDAQ									
Quoting activity									
Market share, %		27.32	42.42	9.77	16.72	0.11	3.66		
Stocks quoted, #		100	100	100	100	40–64	61–98		
Trading activity									
Market share, %		36.41	29.42	23.98	9.90	0.27	0.02		
Average trade size, shares		518	343	292	291	1,375	1,323		
Stocks traded, #		100	100	100	99–100	60–74	37–61		
Panel B: NYSE									
Quoting activity									
Market share, %	36.18	11.85	26.12	2.65		8.71		5.19	9.30
Stocks quoted, #	100	100	99–100	85–93		100		99–100	100
Trading activity									
Market share, %	66.48	18.31	2.91	2.49		3.06		6.21	0.54
Average trade size, shares	1,351	676	301	464		944		458	2,464
Stocks traded, #	100	100	95–100	91–99		99–100		96–100	57–78

intensively. Overall, the three networks originate 68.91% of quotations. AMEX and Chicago appear to have the lowest shares of quotes, while NASDAQ is only second in quoting of its own securities, originating 27.32% of quotations, but has the largest trading share with as much as 36.41% of all executions. Although both AMEX and Chicago rarely participate in trading, their average trade sizes are more than 2.5 times as large as those on NASDAQ and up to 4.5 times as large as those on the ECNs. Goldstein et al. (2007) surmise that orders routed to AMEX and Chicago exchanges are predominantly institutional and may result from preferencing agreements.[11] A possible reason for the ECNs' smaller trade sizes is twofold: first, it could be that a substantial proportion of trades routed to the electronic communications networks is coming from individuals; and second, large orders on ECNs that are being executed against smaller orders are likely to be broken up and reported as smaller trades.

[11]During the sample period, AMEX and Chicago do not quote or trade all sample stocks. Moreover, the Chicago Stock Exchange, at times, participates in trading of more stocks than it quotes. This finding reinforces our belief in the existence of preferencing agreements between Chicago market makers and certain investors.

Panel B of Table 1 provides sample statistics for the NYSE sub-sample. We observe that the NYSE has the highest shares of quotes and trades. The Pacific Stock Exchange is the next most active venue in terms of quote submissions, but its quoting activity does not translate into trading activity (26.12% of quotes compared to only 2.91% of trades). Overall, our findings are consistent with Harris (2003) and Goldstein et al. (2006) who state that ECNs are able to compete successfully for order flow on NASDAQ, but are not as successful on the NYSE.

According to the statistics provided in Table 1, the NYSE executes 66.48% of trades in the NYSE-listed stocks, while NASDAQ only completes 36.41% of trades in the NASDAQ securities. The lower trading share implies that the NASDAQ inter-market is much more fragmented than that for the NYSE stocks and may be prone to frequent locks and crosses. In the next section, we take a closer look at the non-positive NBBO periods on each of the inter-markets.

4. Non-positive spread characteristics

4.1. General view

We use quotes from each market center to reconstruct the national best bid and offer. We find that 15.37% (= 12.34 + 3.03) of NBBOs in the NASDAQ inter-market (Panel A of Table 2) and 4.27% of NBBOs in the NYSE inter-market (Panel B) are non-positive. An average share of zero spreads in the NASDAQ inter-market is over 12%, while a similar share is somewhat lower than 3% in the NYSE inter-market. An examination of negative spreads reveals that 3.03% and 1.39% of, respectively, NASDAQ and the NYSE NBBOs are crossed. We conduct an F test to check whether the daily quantities of non-positive NBBO spreads are consistent across sample days. The results (represented by the p-values) indicate that the daily quantities of locked and crossed quotes do not vary significantly across sample trading days for either sub-sample. Overall, more non-positive spreads occur in the more fragmented NASDAQ than in the more consolidated NYSE inter-market.

Although the shares of non-positive spreads in both sub-samples appear quite high, the issue may not be exceptionally important if locks and crosses end relatively quickly. Table 2 shows that the market for NASDAQ stocks stays locked for an average of 4.83 s and is crossed for 9.93 s; the market for NYSE securities stays locked (crossed) for 7.31 (27.96) s. Overall, non-positive NBBOs are resolved fairly quickly, although crosses last longer than locks. A far more notable fact is the frequency with which these episodes occur. For instance, in the NASDAQ inter-market, an average sample stock is locked or crossed every 1.15 min (68.76 s), whereas in the NYSE inter-market locks and crosses happen every 8.87 min (532.15 s). Thus, although locks and crosses are resolved quickly, they occur rather frequently.

A paired t test discovers significant differences between shares of positive and shares of zero NBBOs on NASDAQ and the NYSE, although shares of crossed NBBOs do not appear statistically different. Thus, although the NASDAQ and the NYSE stocks are affected by locks to different degrees, crosses influence both inter-markets equally. We attribute this finding to the possibility that a significant share of NASDAQ zero spreads may be caused by the ECN traders seeking faster executions and rebates, whereas these traders are not as active in the NYSE stocks.

Table 2

Non-positive NBBOs: holistic view

The table presents results on (i) shares of quotes, (ii) shares of trading time, and (iii) shares of trading volume that correspond to different NBBO types. *p*-Values represent the *F* test results of testing a null hypothesis that the numbers of daily instances are consistent across the sample period for each spread type. *Average time* shows for how long an inter-market usually operates under different NBBOs. *Maximum (minimum) time* summarizes the maximum (minimum) amount of time the NBBOs of different signs last. *Maximum time* results are given as a range, in which the lower bound represents the day with the shortest maximum NBBO period, and the upper bound represents the day with the longest period. The results for *% of time, % of trades*, and *average time* are tested for statistical significance of mean differences between the NASDAQ and the NYSE-sub-samples with the insignificantly different results denoted by the † superscript.

	NBBO > 0	NBBO = 0	NBBO < 0
Panel A: NASDAQ			
% of quotes	84.63	12.34	3.03
p-value	(0.42)	(0.87)	(0.24)
% of time	89.42	8.54	2.04†
% of trades	76.24	19.19	4.57
Average time, s.	68.76	4.83	9.93
Maximum time range, s.	8,864–244	1,179–85	21,347–15
Minimum time, s.	0	0	0
Panel B: NYSE			
% of quotes	95.73	2.88	1.39
p-value	(0.27)	(0.56)	(0.34)
% of time	95.95	2.53	1.52
% of trades	94.21	3.87	1.92
Average time, s	532.15	7.31	27.96
Maximum time range, s	TD* - 1,301	1,494–45	12,043–35
Minimum time, sec.	0	0	0

*TD – trading day.

In terms of elapsed time, zero and negative NBBO episodes account for, respectively, 8.54% and 2.04% of an average trading day in the NASDAQ inter-market, and 2.53% and 1.52% in the NYSE inter-market. From the maximum time range results in Table 2 we also infer that every NASDAQ sample stock is affected by locked or crossed markets: in the cross section, the longest positive NBBO period lasts for 2.46 h (8,864 s) or less than a trading day. In contrast, some of the NYSE sample stocks avoid locks and crosses at least on some days. The next sub-section provides more details on the cross section.

4.2. Cross section

As locking and crossing activity may vary across stocks, we divide the sample into lock (cross) quintiles according to the amount of time a stock is locked (crossed) on an average day, with Quintile 1 consisting of the most actively locked (crossed) securities. In Table 3, for each quintile, we report summary statistics for the time periods, during which stocks are locked (crossed). For each quintile, we also provide percentages of stocks with stable shares of locks (crosses) across the sample period according to an *F* test. We define the shares of locks (crosses) as stable, if they do not exhibit statistically significant differences

Table 3
Lock and cross quintiles

The table contains results of separating the sample into quintiles according to the amount of time the stocks spend being locked or crossed. For each quintile, we compute and report mean, standard deviation, minimum, and maximum shares of an average trading day, during which stocks in the quintile appear locked or crossed; percentage of stocks in the quintile, for which the locked or crossed time shares are stable (do not change significantly across sample days); and quintile averages for number of trades, volume, trade size, price, and market capitalization.

	Time, % of trading day				Stable (%)	# of trades	Volume	Trade size	Price	Market cap., $mil.
Quintile	Mean	St. dev.	Min	Max						
Panel A: NASDAQ Locked										
1	17.61	3.92	13.00	26.03	95	29,826	22,139,839	710	19.03	48,527
2	10.47	1.19	8.62	12.45	100	16,437	6,320,810	397	31.97	18,627
3	7.14	0.68	6.29	8.47	100	9,121	3,001,267	322	35.77	8,781
4	5.16	0.75	4.12	6.25	100	6,425	2,061,662	293	36.46	6,147
5	2.88	0.85	1.38	4.07	100	3,419	813,297	221	53.46	4,459
Panel B: NASDAQ Crossed										
1	8.20	6.89	2.86	27.46	30	17,045	8,485,747	355	41.78	27,674
2	1.81	0.32	1.33	2.56	60	13,464	5,778,912	339	37.23	21,319
3	0.92	0.15	0.70	1.21	75	11,804	5,013,694	345	40.13	10,328
4	0.53	0.11	0.38	0.69	85	12,878	6,583,711	380	30.83	18,931
5	0.20	0.09	0.05	0.37	100	10,037	8,474,812	524	26.71	8,402
Panel C: NYSE Locked										
1	3.69	0.84	2.71	5.18	95	5,507	8,246,094	1,416	37.47	107,871
2	2.18	0.23	1.83	2.70	100	3,503	3,870,555	1,028	45.55	49,242
3	1.61	0.13	1.41	1.82	95	3,043	3,384,958	1,057	46.36	58,575
4	1.14	0.13	0.97	1.38	100	2,929	3,369,974	1,131	47.66	50,077
5	0.64	0.26	0.16	0.95	100	2,015	1,604,473	759	50.74	25,742
Panel D: NYSE Crossed										
1	5.12	5.97	1.06	23.35	65	3,076	3,768,771	1,123	45.34	40,086
2	0.75	0.14	0.56	0.95	85	4,133	5,147,920	1,071	53.03	101,929
3	0.44	0.06	0.35	0.55	90	4,036	4,726,483	1,060	46.08	66,054
4	0.30	0.03	0.26	0.35	100	3,165	3,377,526	1,020	46.90	54,490
5	0.18	0.05	0.05	0.25	100	2,586	3,455,353	1,118	36.43	28,948

across the sample days. In addition, for each quintile, we report average number of trades, trading volume, trade size, price, and market capitalization.

Table 3 shows that susceptibility to locks and crosses varies significantly across quintiles. For instance, Panel A reveals that a NASDAQ stock in quintile 1 is locked 17.61% of the time, whereas a stock in quintile 5 is locked only 2.88% of the time. In the NYSE sub-sample (Panel C), stocks in the most active quintile are locked 3.69% of the time, and those in the least active, 0.64% of the time. Composition of the lock quintiles is notably more stable than that of the cross quintiles, indicating that crosses are more erratic than locks. In particular, for both sub-samples, percentages of stable lock share stocks fluctuate between 95% and 100%, whereas stability of cross shares is comparatively low, with as little as 30% of the stocks having statistically consistent shares in the NASDAQ sub-sample.

Results presented in Table 3 show that trading activity is significantly higher for stocks in highly active lock quintiles. In particular, average daily trading volume for a NASDAQ listed stock in Quintile 1 is 27.22 times higher than that for a stock in Quintile 5. For the NYSE-listed stocks the difference is not as great: volume for the most actively locked securities is only 5.14 times higher than that for the least actively locked ones. A look at the cross quintiles, on the other hand, does not reveal a clear pattern of diminishing trading activity. Although trading volume tends to decrease as we move toward Quintile 5, the decrease is non-monotonic. We also observe that, in almost all cases, stocks with large market capitalizations are the ones with higher time shares of locks and crosses. Overall, our findings lead us to the conclusion that locked and crossed markets are a bigger issue for frequently traded stocks of larger companies on both NASDAQ and the NYSE.[12]

4.3. Initiations and terminations of locks and crosses

We continue our investigation of non-positive NBBOs with an inquiry into how locks and crosses arise and end. The NBBO can be locked or crossed in three manners – active, passive, and simultaneous. A market is actively locked (crossed) by a bid quote when, during a positive NBBO, one venue submits a bid quote that is equal to (higher than) the currently outstanding NBBO ask quote posted more than one second ago.[13] Conversely, a passive lock happens when a market for a security is coming out of a cross. If while the market is crossed, a venue submits a quote that has the potential of locking the market, this quote may stay dormant until the cross is resolved. If subsequently one of the crossing venues withdraws its quote and ends the cross, the passive quote may become active and lock the market.[14] Finally, a simultaneous lock (cross) is a result of two venues' concurrent, or within one second, posting of NBBO quotes with the offer equal to (lower than) the bid. A simultaneous lock (cross) is an example of a lack of coordination among market centers. The data in Table 4 show that simultaneous locks and crosses represent more than 20% of non-positive spread originations in the NASDAQ and more than 8% of originations in the NYSE inter-markets. The majority of lock (cross) initiations are, however, active, with as many as 72.79% (68.19%) of instances in the NASDAQ and 83.27% (91.26%) of instances in the NYSE inter-markets.

In the NASDAQ inter-market, the highest fraction of quotes that actively lock the market, 28.10%, comes from ArcaEx (Panel A of Table 4). Instinet and NASDAQ also enter significant numbers of quotes that lead to active locks and crosses, respectively, 25.07% and 10.93% of locking and 17.36% and 14.37% of crossing quotes. NASDAQ is most often affected by active locks, 26.01% of all active inter-market cases, whereas AMEX is most often affected by active crosses, 19.65% of all active cases. Chicago is least affected by either type of non-positive spreads, likely because the exchange is rarely at the NBBO. The leading locking venue, ArcaEx, appears to be the most active in terminating locked episodes — it unlocks the NBBO in 22.71% of cases. Instinet and NASDAQ follow with, respectively, 20.03% and 18.85% of unlocks. A similar pattern is found for

[12]We find that, similar to the intraday volume patterns, the intraday patterns of lock and cross initiations are U-shaped (not tabulated).

[13]A lock (cross) by an ask quote occurs when one venue submits an ask quote that is equal to (less than) the current NBBO bid quote posted more than one second ago.

[14]A dormant crossing quote may be submitted while the market is already crossed by a quote submitted earlier. If the dormant quote is still active after withdrawal of the first quote, the NBBO will continue to be crossed. We do not identify such consecutive crosses as a separate category.

Table 4

Locking (crossing), locked (crossed), and unlocking (uncrossing) statistics

The table contains statistics on shares of lock and cross initiations (locking and crossing), shares of appearing on the passive side of such initiations (locked and crossed), and shares of lock and cross terminations (unlocking and uncrossing). Active locks (crosses) are initiated by NBBO quotes, posted at least two seconds after the locked quote(s), that are equal to (are lower than if ask quotes, or higher than if bid quotes) the outstanding NBBO quote on the other side. Passive locks arise when markets come out of crosses, if a venue posts a locking quote during the cross, and this locking quote becomes part of the NBBO after the market uncrosses. Simultaneous locks (crosses) are initiated by quotes posted within the same (or two subsequent) second(s). In Panels A and B, locking (crossing), locked (crossed), and unlocking (uncrossing) records are broken up across venues to add up to shares of active initiations. Also in Panels A and B, we provide information on each venue's share of the NBBO quotes. In Panels C and D, we include an additional statistic, "Active positive," that measures intensity of each of the venue's involvements in positive NBBOs.

	NBBO quotes	Active positive	Locking	Locked	Unlocking	Crossing	Crossed	Uncrossing
Panel A: NASDAQ, market share of non-positive NBBO initiations and terminations, %								
NASDAQ	30.12		10.93	26.01	18.85	14.37	17.20	14.50
Pacific (ArcaEx)	44.61		28.10	15.26	22.71	25.76	8.56	15.67
National (Island)	6.84		7.21	9.29	9.50	7.26	6.62	6.00
ADF (Instinet)	16.91		25.07	17.18	20.03	17.36	11.51	16.43
Chicago	0.03		0.02	0.22	0.56	0.03	0.30	1.62
AMEX	1.49		1.46	8.91	5.33	3.41	19.65	10.03
Active			72.79	76.86	76.98	68.19	63.84	64.25
Passive			7.05	3.88	—	—	—	—
Simultaneous			20.16	19.26	23.02	31.81	36.16	35.75
Panel B: NYSE, market share of non-positive NBBO initiations and terminations, %								
NYSE	63.18		51.55	32.10	36.37	59.37	57.12	11.53
NASDAQ	7.51		9.52	14.43	7.59	6.89	7.92	8.51
Pacific	28.23		21.03	26.07	23.31	23.62	13.44	13.54
National	0.25		0.36	3.71	7.41	0.30	3.25	14.10
Chicago	0.21		0.37	2.02	5.75	0.49	2.83	10.47
Boston	0.46		0.28	3.70	6.08	0.58	5.98	10.63
Philadelphia	0.15		0.16	0.92	6.65	0.01	1.73	10.80
Active			83.27	82.95	93.16	91.26	92.27	79.58
Passive			5.27	4.18	—	—	—	—
Simultaneous			11.46	12.87	6.84	8.74	7.73	20.42
Panel C: NASDAQ, non-positive spread initiations and terminations as % of NBBO quotes by venue								
NASDAQ		99.51	0.41	1.52	0.73	0.08	0.12	0.05
Pacific (ArcaEx)		99.22	0.67	0.55	0.45	0.11	0.08	0.03
National (Island)		98.61	1.23	2.18	1.39	0.16	0.19	0.09
ADF (Instinet)		98.13	1.64	1.36	1.28	0.23	0.28	0.03
Chicago		97.89	1.38	41.35	8.72	0.73	11.39	0.22
AMEX		97.12	2.04	12.02	8.67	0.84	3.38	1.83
Panel D: NYSE, non-positive spread initiations and terminations as % of NBBO quotes by venue								
NYSE		99.04	0.83	0.43	0.36	0.13	0.07	0.09
NASDAQ		98.68	1.21	2.77	2.76	0.11	0.33	0.13
Pacific		99.14	0.74	0.94	1.12	0.12	0.13	0.09
National		97.99	1.69	18.62	6.78	0.32	3.29	0.27
Chicago		98.23	1.42	11.28	6.39	0.35	3.25	0.43
Boston		98.19	1.38	20.56	12.28	0.43	5.63	1.11
Philadelphia		99.13	0.80	11.24	5.76	0.07	4.21	0.20

uncrosses, with Instinet, ArcaEx, and NASDAQ terminating comparable shares of crosses of about 15% each.

While NASDAQ is only third in intensity of locking and crossing of its own intermarket, the NYSE seems to cause the majority of non-positive spreads (Panel B of Table 4). In particular, the exchange initiates 51.55% of locked and 59.37% of crossed cases. The Pacific Stock Exchange and NASDAQ also actively participate in the origination of non-positive spreads with 21.03% and 23.62% of, respectively, locked and crossed markets caused by the former, and 9.52% and 6.89% by the latter. The NYSE- and Pacific-originated quotes are subject to most locked instances: respectively, 32.10% and 26.07%. NASDAQ quotes are locked in 14.43% of cases, which makes it the third most affected venue. The NYSE gets its quotes crossed the most, with 57.12% of instances; followed by Pacific, 13.44%; and NASDAQ, 7.92%. Zero spread periods are most often ended by the NYSE, 36.37%; Pacific and NASDAQ end, respectively, 23.31% and 7.59% of locks. The other markets follow closely with shares of unlocks ranging from 7.41% on National to 6.08% on Boston. Crossed markets are most often ended by National, 14.10% of cases, closely followed by the other market centers.

It should not come as a surprise that market centers that generate the majority of quotes also initiate a lot of non-positive spreads. Thus, although instructive in terms of competitive landscape, results in Panels A and B are uninformative regarding the pace of initiations relative to the venues' NBBO involvement. We therefore calculate fractions of lock- and cross-initiating quotes in the number of NBBO quotes posted by each of the sample venues (e.g., locking quotes from ArcaEx comprise 0.67% of all NBBO quotes posted by ArcaEx) and present the results in Panels C and D. We find that the differences in intensities of non-positive NBBO initiations among venues are quite subtle, with the shares of lock-causing quotes ranging from 0.41% on NASDAQ to 2.04% on AMEX. Generally, none of the self-regulatory organizations (SROs) can be blamed for initiating locks and crosses more actively than the others.

The data show notably different patterns when we investigate intensities of being locked and crossed. We find that as much as 41.35% and 11.39% of Chicago NBBO quotes are, respectively, locked and crossed. Although not as dramatic, similar statistics are observed for AMEX, on which 12.02% and 3.38% of NBBO-forming quotes are, respectively, locked and crossed. The rest of the market centers do not show any strong patterns of being locked or crossed. Finally, the data show that AMEX and Chicago are relatively active in terminating the locks: 8.67% of AMEX and 8.72% of Chicago NBBO quotes terminate zero spread periods. The results for crossed markets are much less pronounced, although the two exchanges are, once again, the most active in ending of non-positive spreads.

In the NYSE sub-sample, intensity of initiations is similar to that in the NASDAQ sub-sample — neither venue can be identified as a particularly active initiator of non-positive spreads (Panel D of Table 4). A clearer pattern can be seen for the lockees: the exchanges being locked the most are Boston (20.56%), National (18.62%), Chicago (11.28%), and Philadelphia (11.24%). Boston terminates 12.28% of zero spreads, followed by National, Chicago, and Philadelphia that carry out, respectively, 6.78%, 6.39%, and 5.76% of lock terminations. Intensity of lock terminations is often half of the intensity of being locked (i.e., Boston is locked in 20.56% of cases, but only ends 12.28% of the instances). The possible reason for this phenomenon is twofold. First, as we show later, zero spread periods are often ended by the initiators. Second, while multiple market centers may have their quotes locked or crossed at the same instance; ending of non-positive spreads is

Table 5
Lock (cross) instances and autoquotes (100-share quotes)

The table contains percentage shares of locks and crosses based on the depth of quotes involved. We consider instances in which locked (crossed) depth (e.g., depth maintained by the locked (crossed) market) is 100; 100–501; and more than 501 shares, as well as instances where locking (crossing) depth (e.g., depth maintained by the locking (crossing) market) is 100 shares. "All" record contains the shares of lock (cross) instances across all markets. We also report the shares for each market individually. In the "Autoquotes at NBBO, %" column, we calculate the share of autoquotes in all NBBO quotations submitted by the venues. The *p-values* indicate the results of testing a null hypothesis that percentage shares across sample venues are identical.

	Autoquotes at the NBBO, (%)	Locked depth, shares			Locking depth, shares	Crossed depth, shares			Crossing depth, shares
		100	101–500	501+	100	100	101–500	501+	100
Panel A: NASDAQ									
All	16.75	22.78	29.18	48.04	32.11	26.14	34.13	39.73	37.18
NASDAQ	22.06	30.95	29.22	39.83	40.52	46.37	32.66	20.97	51.75
Pacific (ArcaEx)	12.61	19.42	27.56	53.02	30.37	25.09	35.34	39.56	32.23
National (Island)	25.96	29.99	31.07	38.94	36.83	40.31	35.67	24.02	55.34
ADF (Instinet)	16.47	20.93	32.36	46.71	31.71	29.72	39.54	30.74	35.82
Chicago	13.96	16.94	19.73	63.33	47.30	43.03	15.76	41.21	0.07
AMEX	1.04	1.30	26.08	72.62	0.99	1.82	31.49	66.70	1.29
p-value	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Panel B: NYSE									
All	21.92	0.12	95.38	4.50	0.54	0.15	99.80	0.05	0.74
NYSE	22.09	0.28	93.24	6.48	0.84	0.36	99.43	0.21	1.10
NASDAQ	25.69	0.01	98.91	1.08	0.12	0.07	99.93	0.00	0.18
Pacific	22.76	0.00	94.73	5.27	0.04	0.00	100.00	0.00	0.11
National	61.62	0.00	98.21	1.79	0.00	0.00	100.00	0.00	0.00
Chicago	13.82	0.52	93.60	5.89	3.06	0.25	99.75	0.00	0.00
Boston	12.54	0.22	95.01	4.77	0.61	0.27	99.73	0.00	0.00
Philadelphia	16.02	0.39	89.88	9.72	0.00	0.00	100.00	0.00	0.00
p-value	0.00	0.27	0.00	0.00	0.14	0.21	0.38	0.53	0.12

typically done by only one SRO. In particular, a locked (crossed) episode may only end when all locked (crossed) venues have updated their quotes, therefore only the last venue to withdraw the stale quote is recognized as the unlocking (uncrossing) venue.

4.4. Autoquotes

At the time of our study, the Intermarket Trading System (ITS) rules indicate that NYSE inter-market participants are not required to honor 100-share NBBO quotes and can trade through them, as these are likely to be placeholder (non-economic) quotes. Thus, while the NYSE inter-market may seem locked or crossed, the situation may be due to 100-share autoquotes that markets can ignore.[15] As shown in Panel B of Table 5, for the NYSE-listed stocks, the share of non-positive NBBOs originated when a locked/crossed

[15]We are grateful to the anonymous referee for suggesting we explore this issue.

quote has a depth of 100 shares is only 0.12% of lock and 0.15% of cross instances. The vast majority of locks and crosses on the NYSE happen when the locked quote is between 101 and 500 shares deep. An F test shows that these results are consistent across sample venues, with no venue's shares of locked or crossed autoquotes exceeding 1%.

In the NASDAQ sub-sample (Panel A of Table 5), the incidence of non-positive NBBO originations that involve 100-share quotes is substantially higher than that shown above for the NYSE inter-market — respectively, 22.78% of locked and 26.14% of crossed instances. This result is expected, since in the NASDAQ inter-market, autoquotes are as legitimate as all other quotes and cannot be ignored. We also consider instances in which the depth of a locking (crossing) quote equals 100 shares and find that results for NASDAQ and the NYSE are relatively similar to those for the locked (crossed) autoquotes. In the NYSE inter-market, only 0.54% (0.74%) of locking (crossing) quotes have depths of 100 shares; whereas in the NASDAQ inter-market, 32.11% (37.18%) of locking (crossing) quotes are for 100 shares.

Our investigation of autoquotes would be incomplete if we did not show the incidence of 100-share quotes during all NBBOs to facilitate comparison. We therefore estimate shares of autoquotes at the NBBO in the total number of NBBO-forming quotes from each venue. Results are presented in the "Autoquotes at NBBO, %" column of Table 5. Although 100-share quotes in the NYSE sub-sample are rarely involved in non-positive NBBOs, it appears that posting of such quotes is not a rare occasion. In fact, autoquotes are a part of, on average, 21.92% of the NBBOs. The proportions are of a similar magnitude in the NASDAQ inter-market, in which 16.75% of the NBBO quotes are for only 100 shares. As opposed to the NYSE, NASDAQ autoquotes are actively involved in origination of non-positive NBBOs: with only 16.75% participation share, these quotations are locked (locking) in 27.78% (32.11%) of instances and are crossed (crossing) in 26.14% (37.18%) of instances.

The phenomenon of locks and crosses that involve 100-share quotes appearing in such different proportions in the two sub-samples may be attributed to the very issue that originated the inquiry — the fact that 100-share quotes can be ignored in the NYSE inter-market. Since these quotes can be disregarded by participating venues, there is no sense in locking or crossing them. The same reasoning applies to the fact that a very small percentage of locking and crossing quotes have a 100-share depth. Since other venues are entitled to ignore these quotes, they become useless according to all of our hypotheses. On the contrary, in the NASDAQ inter-market, traders may not ignore the 100-share quotes and may choose to lock or cross them instead, corroborating our earlier suggestion that some locks and crosses on NASDAQ are proactive steps to force action and not just a signal of interest.

4.5. Removal of locks and crosses

NASDAQ dealers often stress that they are the ones to end locked and crossed markets initiated by the ECN traders who implicitly exploit liquidity providers on other venues while seeking access fee rebates and/or faster executions. In Table 6, we provide evidence on the issue of terminating non-positive NBBOs by the lockers (crossers) and lockees (crossees).[16] The results show that initiators end locks and crosses in only about 52% cases,

[16]Because ECN activity on the NYSE is significantly smaller than that on NASDAQ, we do not include the NYSE sub-sample results in Table 6.

Table 6
Unlocking (uncrossing) by locking (crossing) and locked (crossed) venues: NASDAQ sub-sample

The table investigates instances of unlocking (uncrossing) divided into those performed by locking (crossing) and locked (crossed) venues. Results are shown as percentage shares of all unlock (uncross) cases. We first provide aggregate shares of unlocks (uncrosses) by the locking and locked venues for the entire inter-market and then separate the shares across venues. The results are tested for statistical significance of differences in percentage shares among SROs. The only insignificant difference is that between uncrossed-by-crossed shares of Pacific and ADF.

	Unlocked by, %		Uncrossed by, %	
	Locking venue	Locked venue	Crossing venue	Crossed venue
Overall	51.64	48.36	51.84	48.16
NASDAQ	7.46	20.31	12.36	14.07
Pacific (ArcaEx)	16.91	5.84	17.78	4.36
National (Island)	5.35	4.23	3.12	1.32
ADF (Instinet)	19.28	7.69	10.74	5.18
Chicago	0.01	0.18	0.01	0.05
AMEX	2.63	10.11	7.83	23.18

corroborating the dealers' claims. Furthermore, when we look at the statistics by SRO, we discover a rather visible pattern that confirms that dealers and specialists end more locks (crosses) after being locked (crossed) than after initiating locks (crosses). For instance, NASDAQ ends 20.31% of zero spread instances after being locked and only 7.46% after locking others. On the contrary, the majority of terminations performed by the ECNs occur when the networks initiate non-positive NBBOs, suggesting that the networks extensively unlock (uncross) NBBOs that they lock (cross) by withdrawing locking (crossing) quotes, possibly after execution of locking (crossing) orders.

Whether locks (crosses) end after sufficient volume is executed on the locking (crossing) or locked (crossed) venues is an empirical question. We observe that trading on a locked or a crossed venue does not accompany every non-positive NBBO instance. Results in Table 7 show that, in the NASDAQ inter-market, only about 50.66% ($= 22.88 + 27.78$) of locked and 42.76% ($= 23.78 + 18.98$) of crossed cases are accompanied by trading. On the NYSE, the shares of locked and crossed instances are, respectively, 26.92% and 33.32%. Collectively, in 50 and more percent of locked and crossed instances, a trade does not precede withdrawal of locking or crossing quotes, indicating that either a locking (crossing), a locked (crossed), or both quotes are withdrawn or cancelled without trading.

We next look at situations in which enough volume to deplete the locking depth is transacted on either the locking (crossing) or locked (crossed) venue before the market is unlocked (uncrossed). Table 7 shows that only 21.99% (17.98%) of NASDAQ and only 15.22% (22.49%) of the NYSE locks (crosses) are resolved after sufficient volume is transacted on either locking (crossing) or locked (crossed) venue, indicating that, in both sub-samples, more than 75% of non-positive spread instances are resolved without sufficient trading. Although this finding contradicts our perception of non-positive NBBOs as trading tools, we point out that not all locks and crosses must necessarily serve their original purpose. A portion of such orders may be fleeting orders that, as suggested by Hasbrouck and Saar (2005), sweep the market for liquidity during significant informational events and are often cancelled without execution if sufficient liquidity is not found.

Table 7
Trading and removal of non-positive NBBOs

The results contain percentage shares of instances in which any trading or trading sufficient to remove a locking (crossing) quote occurs on a locking (crossing) or a locked (crossed) venue prior to the quote removal. Records "Trade on" contain shares of instances, during which any volume (not necessarily sufficient to deplete the locking (locked) or crossing (crossed) quote) is executed on the locking (locked) or the crossing (crossed) venue. Record "Locking (Crossing) quote depleted by volume on" contains shares of instances resolved after volume sufficient to deplete a locking (crossing) quote is executed on either the locking (crossing) or the locked (crossed) venue. Record "Locked (Crossed) quote depleted by volume on" contains shares of instances resolved after sufficient volume to deplete a locked (crossed) quote is executed on either the locking (crossing) or locked (crossed) venue.

	Trade on		Locking quote depleted by volume on		Locked quote depleted by volume on		Trade on		Crossing quote depleted by volume on		Crossed quote depleted by volume on	
	Locking venue	Locked venue	Locking venue	Locked venue	Locking venue	Locked venue	Crossing venue	Crossed venue	Crossing venue	Crossed venue	Crossing venue	Crossed venue
Panel A: NASDAQ												
All	22.88	27.78	11.78	10.21	3.53	6.09	23.78	18.98	11.14	6.84	2.36	4.84
NASDAQ	16.00	14.62	8.83	7.93	4.29	8.06	17.81	14.96	10.29	7.13	3.91	5.08
Pacific (ArcaEx)	21.80	15.56	10.02	5.10	2.20	3.01	25.75	21.10	11.35	6.52	2.92	4.14
National (Island)	49.34	45.69	22.42	10.27	1.02	7.79	54.78	57.38	23.70	15.66	1.42	5.81
ADF (Instinet)	23.80	14.62	13.13	5.14	3.88	4.81	21.89	20.06	10.20	7.66	2.18	2.65
Chicago	20.27	11.87	10.81	7.39	1.00	1.82	23.81	9.90	23.81	8.69	0.92	3.40
AMEX	0.14	0.09	0.01	0.02	0.07	0.04	0.00	0.07	0.06	0.04	0.03	0.07
Panel B: NYSE												
All	14.72	12.20	8.32	6.90	1.93	2.08	18.74	14.58	10.94	11.55	2.15	2.72
NYSE	18.73	15.49	7.57	7.37	2.01	2.92	17.33	13.60	7.71	6.36	1.42	1.28
NASDAQ	10.81	10.46	9.80	9.14	2.81	2.05	22.32	15.07	17.68	11.58	3.85	1.79
Pacific	4.57	4.86	4.10	3.44	0.29	0.82	16.30	11.30	13.03	8.11	2.09	2.31
National	4.12	5.65	3.12	2.53	0.72	0.93	14.71	9.54	10.21	7.38	2.66	2.63
Chicago	2.04	5.82	5.37	1.53	0.01	0.12	2.78	6.36	2.08	5.09	0.01	0.02
Boston	7.88	13.01	10.16	6.67	1.57	1.63	8.51	18.35	6.38	17.68	0.01	0.01
Philadelphia	0.03	1.92	1.31	0.02	0.01	0.04	0.00	0.39	0.00	0.39	0.00	0.00

Another issue that we consider in Table 7 has to do with locations of trade executions. We observe that, in the majority of cases, trading that depletes locking quotes occurs on locking venues, especially ECNs, once again corroborating the dealers' claims mentioned earlier. For instance, 22.42% of locking quotes originated on Island are withdrawn after Island executes sufficient volume to deplete these quotes, whereas only 10.27% of Island locking quotes are withdrawn after sufficient volume is executed on the locked venues. This result is consistent with our hypothesis that traders who lock and cross the NBBO often do so to get orders routed to their base venue instead of sending their orders elsewhere. Although unexpected, substantial shares of locking (crossing) quotes withdrawn after sufficient trading on locked (crossed) venues may be attributed to the fact that trading on these venues is not necessarily related to depletion of locking (crossing) quotes.[17]

Finally, in Table 7, we consider whether enough volume is transacted on either venue to deplete the locked (crossed) quote and prompt its withdrawal instead of withdrawal of the locking (crossing) quote. We account for the fact that, by the time a quote is locked (crossed), it could already be partially taken out by trades preceding the lock (cross). Therefore, for non-positive NBBOs terminated by withdrawal of the locked (crossed) quotes, we add the volume executed on the locked (crossed) venue prior to a lock (cross) to the volume executed on either SRO during the lock (cross). Results indicate that 9.62% (= 3.53 + 6.09) and 7.20% (= 2.36 + 4.84) of, respectively, locks and crosses in the NASDAQ sub-sample are terminated by depletion of locked and crossed quotes; in contrast, the figures for the NYSE sub-sample are, respectively, 4.01% and 4.87%. Collectively, although Table 6 shows that almost one half of non-positive NBBOs are terminated by the locked and crossed venues, results in Table 7 reveal that the majority of these terminations are, apparently, caused by quote withdrawals not preceded by trades.[18]

We do not present all results on withdrawals related to trading in Table 7, since the validity of some of the findings may suffer from our inability to correctly identify locations of quote depletion. For instance, we do not report results for occasions when volume sufficient to deplete a locking(ed) or crossing(ed) quote is executed on all venues involved in a lock or a cross combined. Furthermore, in some cases, we cannot decisively determine trading on which venue depletes the initiating quote. For instance, a number of locks and crosses in our sample are not terminated immediately after sufficient (or often even more than sufficient) volume is executed on either locking (crossing), or locked (crossed) venue, but instead are terminated later, after insufficient volume is executed on the opposite venue.[19] In order to avoid inaccuracies related to the issues identified above, we limit the

[17]According to the ITS rules, the venue-receiver of an order reports the trade and is recorded in TAQ as the venue that carried out the trade.

[18]We also conduct an investigation of withdrawals of stale quotes. If a quote is truly stale, it is likely to be withdrawn without trading, as the lockee may not be willing to trade at an outdated price represented by such a quote. Empirical results confirm this notion (not tabulated), as 5–7-min old quotes are withdrawn without sufficient volume 98% of the time, and quotes older than 7 min are withdrawn without sufficient volume almost all the time.

[19]For instance, venue A's quote is locked by venue B's 500-share quote. In some situations, we observe the following: after the lock, venue B executes one or several trades for a total volume of (more than) 500 shares, but does not unlock the market. During the next several seconds, locked venue A executes trades for a total of less than 500 shares, after which venue B withdraws the locking quote. In cases like this, we refrain from assigning either venue as the one on which the lock is depleted, since we cannot be sure whether venue B is simply tardy unlocking or if partial depletion occurs on venue A.

lock (cross) instances that we report in Table 7 to those for which we can identify the venues that deplete locking (locked) quotes with certainty.

5. Price changes, trading, and market quality

5.1. Price changes

Buying and selling may cause different effects on volatility contingent on the direction of preceding price moves. In particular, Avramov, Chordia, and Goyal (2006) show that, subsequent to price declines, an influx of non-informational sell orders causes an increase in volatility. This phenomenon is asymmetric and does not replicate for price increases. Avramov et al. suggest that prices in rising markets are less volatile, because contrarian trades partly offset excessive demand of herding trades. We extend this argument by suggesting that aggressive selling by herding traders during periods of falling prices may lead to excessive generation of locks and crosses by ask quotes and may not lead to a similar generation of locks and crosses by bid quotes when prices rise, due to greater liquidity provided by the contrarian traders. To shed some light on this matter, we separate locks and crosses initiated by ask quotes (sell orders) from those initiated by bid quotes (buy orders).[20] Consistent with the aforementioned suggestion, Table 8 shows that proportions of ask-initiated locks and crosses in the NASDAQ inter-market exceed those of bid-initiated by, respectively, 9.06% and 2.80%. The figures, however, appear reversed in the NYSE inter-market, with shares of bid-initiated locks and crosses exceeding those of ask-initiated by, respectively, 4.14% and 1.98%. Thus, we cannot decisively state that more non-positive NBBOs are originated by either ask or bid quotes.

We next examine ask- and bid-initiated locks (crosses) contingent on preceding and following price changes. We expect the majority of ask-initiated locks (crosses) to follow negative price changes, since when prices are falling traders may use ask-initiated locks (crosses) to expedite executions in the inter-market setting. By the same token, bid-initiated locks (crosses) are expected to follow price increases. As to the price changes subsequent to locks and crosses, we expect the pre-lock (-cross) trends to continue, as our hypotheses suggest that non-positive spreads are not the causes of the price moves, but rather the consequences. We find that the data generally support the aforementioned suggestions, as the results show that locks by asks (bids) are most often preceded and followed by negative (positive) price changes. For instance, consistent with our predictions, Table 8 shows that 23.75% (26.38%) of locks in the NASDAQ inter-market are initiated by an ask quote posted after a decrease in price during the preceding 10 (50) trades. At the same time, ask quotes generate as little as 12.08% (9.17%) of locks initiated after an increase in price during the preceding 10 (50) trades. This result holds for locks and crosses on both inter-markets, and percentage shares of ask-initiated (bid-initiated) non-positive NBBOs that follow or precede price declines (increases) are statistically larger than those that follow or precede price increases (declines) in all but one case.

Table 8 also contains shares of price changes that occur *during* ask- and bid-initiated locks and crosses. We find that, in most cases, no price change occurs during non-positive NBBO episodes on both inter-markets. For instance, prices do not change during 69.44% (= 37.25 + 32.19) of locked episodes in the NASDAQ inter-market. We confirm, however,

[20] We thank the anonymous referee for suggesting we take this route.

Table 8
Price changes and non-positive NBBOs

The table contains percentage shares of zero and negative NBBOs initiated by ask and bid quotes in various circumstances. We first present the overall shares of locks and crosses originated by ask and bid quotes on each inter-market. Afterwards, we consider how locks (crosses) by ask and bid quotes depend on previous price changes. In particular, we divide shares of ask- and bid-initiated locks (crosses) into those that occur after a negative, zero, or a positive price change over preceding 10 and 50 trades. Next, we present shares of ask- and bid-initiated quotes separated according to price changes during locked and crossed periods, and finally, we present price changes 10 and 50 trades after locks and crosses are resolved. Price changes are defined as follows: price change during 10 (50) preceding trades equals the last trade price before a lock (cross) minus the trade price of the -10th (-50th) trade preceding the pre-lock (-cross) trade. Price change during a lock (cross) is defined as the price of the last locked (crossed) trade minus the price of the first locked (crossed) trade. Price change following the lock (cross) is calculated as the price of the +10th (+50th) trade after a lock (cross) minus the price of the first after-lock (-cross) trade. According to the paired *t* tests, all ask- and bid-initiated shares following, accompanying, or preceding price declines and increases are statistically different, with the shares of bid-initiated crosses preceding the 10-trade price change on the NASDAQ inter-market being the only insignificantly different pair indicated by the superscript †.

	NASDAQ				NYSE			
	Locked by		Crossed by		Locked by		Crossed by	
	Ask	Bid	Ask	Bid	Ask	Bid	Ask	Bid
Overall	54.53	45.47	51.40	48.60	47.93	52.07	49.01	50.99
Preceding 50 trades								
$-\Delta$ P	26.38	8.17	30.12	12.60	27.78	12.78	36.87	9.15
$+\Delta$ P	9.17	20.28	11.70	23.63	11.66	28.65	8.47	34.20
No Δ P	18.94	17.05	10.74	11.22	9.11	10.02	5.44	5.86
Preceding 10 trades								
$-\Delta$ P	23.75	10.37	25.37	14.09	24.05	14.58	30.37	12.08
$+\Delta$ P	12.08	18.74	13.43	21.42	13.49	25.81	11.10	30.68
No Δ P	18.70	16.35	12.61	13.08	10.41	11.66	7.56	8.20
During lock (cross)								
$-\Delta$ P	12.31	3.93	21.02	7.79	7.25	4.34	11.62	9.03
$+\Delta$ P	4.55	9.78	8.41	15.92	5.00	7.06	9.66	11.24
No Δ P	37.25	32.19	24.42	22.45	36.53	39.81	28.92	29.53
Following 10 trades								
$-\Delta$ P	21.48	13.49	22.37	18.40†	20.74	17.08	23.90	18.19
$+\Delta$ P	16.78	17.86	18.29	19.62	16.09	23.25	17.08	24.66
No Δ P	16.32	14.07	10.56	10.76	11.21	11.62	8.03	8.14
Following 50 trades								
$-\Delta$ P	28.00	5.10	39.34	9.37	27.37	10.86	29.26	6.44
$+\Delta$ P	5.88	20.96	5.88	26.03	9.25	32.28	7.36	38.16
No Δ P	21.36	18.70	10.14	9.24	10.30	9.93	9.69	9.10

that shares of price declines (increases) are higher than those of increases (declines) during non-positive NBBOs caused by ask (bid) quotes. For example, in the NASDAQ inter-market, 12.31% of locked-by-ask markets are accompanied by price declines; whereas only 4.55% of these markets are accompanied by price increases.

Our hypotheses rely on the assumption that locked and crossed markets accompany significant price shifts. Although Table 8 confirms that such shifts exist, it does not provide

Table 9
Intensity of price changes

For both sub-samples, we calculate two measures of price contribution: mean price contribution (MPC) and intensity of price contribution (IPC). MPC is calculated for each stock on each sample day as a share of absolute price change during a particular NBBO type in that day's aggregate absolute price change. IPC is computed as a share of absolute price change attributable to a particular NBBO type in daily price change divided by the amount of time the NBBO type is active on the particular day. The measure is then aggregated similarly to the MPC. The differences across all NBBO types are statistically significant as indicated by the paired t tests.

	NBBO$>$0	NBBO $=$ 0	NBBO$<$0
Panel A: NASDAQ			
Mean price contribution	1.1450	0.6963	0.3205
Intensity of price contribution, per minute	0.0041	0.0315	0.2981
Panel B: NYSE			
Mean price contribution	0.9116	0.2914	0.2910
Intensity of price contribution, per minute	0.0038	0.0492	0.2637

evidence on their magnitude. To shed additional light on the issue, we adopt a procedure similar to that of Cao et al. (2000) who use the relative time-weighted price contribution to measure the strength of signals corresponding to different NBBO types during the NASDAQ pre-opening. Our data set is notably different from that of Cao et al., as it includes multiple short periods of non-positive spreads that occur during the trading day. Therefore, we use two modified measures of price contribution: MPC (mean price contribution) and IPC (intensity of price contribution). Mean price contribution is calculated for each stock on each sample day as a share of absolute price change during a particular NBBO type in that day's aggregate absolute price change. The daily shares are then aggregated across trading days and across stocks. Absolute price changes are used, since Table 8 shows that locked and crossed markets may accompany falling as well as rising prices regardless of the originating quote. To prevent this phenomenon from cluttering the MPC measure, we remove the sign from price changes by taking their absolute value. MPC in Table 9 reveals that most price changes accumulate during positive NBBOs, which is expected since these NBBOs occupy the majority of the sample time.

The MPC measure does not account for the length of non-positive spread periods. Although the results show that price changes normally occur during the positive NBBOs, the question is: How intensive are the price shifts, if the length of different NBBO periods is taken into account? To investigate this issue, we compute IPC as a share of absolute price change attributable to a particular NBBO type in daily price change divided by the amount of time the NBBO type is active on the particular day. The measure is then aggregated similarly to the MPC. By taking into account the length of NBBO types, we are able to show that crossed markets accompany the most intensive price shifts on both NASDAQ and the NYSE. In particular, the IPC for negative NBBO spreads is 0.30 and 0.26 on NASDAQ and the NYSE inter-markets, respectively. The changes are not as intense during locked NBBOs, with ratios of 0.03 and 0.05. Positive spread periods are the least intense, with the ratios of about 0.004 in both inter-markets.

5.2. NASDAQ trading

Earlier sections show that instances of non-positive spreads make up a nontrivial portion of an average trading day, especially in the NASDAQ inter-market. In Table 10, we take a closer look at trading during the non-positive NBBO episodes. In Panel A, we present results similar to those in Table 1, but differentiate between the NBBO types. We find that while NASDAQ's market share rises from 36.18% to 40.51% when the NBBO changes sign from positive to negative, shares of Island and ArcaEx fall from 25.12% and 28.73% to 21.83% and 27.47%, respectively.

We also find that trading intensifies during non-positive spread periods. In the NASDAQ inter-market, the number of trades increases from an average of 9/min during positive NBBOs to 15/min during zero spreads, a 1.67-time increase (Panel B of Table 10). The results for crossed markets are even more impressive, with the inter-market executing as many as 57 trades during 1 min of negative spreads — more than a six-fold increase as compared to executions during positive NBBOs. These results confirm our earlier suggestion that locks and crosses often accompany significant price shifts that, in turn, are often accompanied by increases in volume and trading frequency. Average trade size is lower during the non-positive NBBO periods on almost all venues (Panel C of Table 10). In particular, the average trade size falls from 395 to 371 shares during the locked markets and further to 322 shares during the crossed markets. This nearly universal decrease is consistent with the fact that a number of non-positive NBBOs are caused by ECN marketable limit orders. Since an average ECN trade is smaller than that on the other SROs, trade sizes go down when trading against the locking (crossing) orders intensifies. The trade size decrease may be also attributed to the strategic behavior of market participants who execute smaller trades during uncertain times accompanied by non-positive NBBOs.

5.3. NYSE trading

In the NYSE sub-sample, trading shares of some of the venues exhibit notable changes during the locked and crossed periods (Panel D of Table 10). For instance, the NYSE loses about 15% of volume when the NBBO goes from positive to zero. On the other hand, market shares on Pacific and NASDAQ go up by about 6% during zero spreads and by 11.51% on Pacific (by 3.59% on NASDAQ) during negative spreads. The rest of the NYSE rivals also show increases in market shares when going from positive to zero NBBO spreads.

Trading frequency in the NYSE inter-market increases during non-positive spread periods, but not as much as that in the NASDAQ inter-market. In particular, in Panel E of Table 10 we observe a 1.4-time increase in trading frequency during the locked markets and a 1.8-time increase during the crossed markets. Average trade sizes for the NYSE sub-sample do not appear as uniform as those for the NASDAQ inter-market (Panel F of Table 10). The trade sizes on Boston, NYSE, and Chicago are higher during non-positive NBBOs; however, on Pacific, NASDAQ and Philadelphia, trade sizes decrease when the spreads acquire a negative sign. On average, trade sizes in the NYSE sub-sample increase by about 20% during zero spreads and almost two-fold during the negative NBBOs. Although inconsistent with the findings for NASDAQ, a different trade size pattern on the NYSE does not contradict our main line of thinking — ECNs are not as active in the

Table 10
Trading during positive, zero, and negative NBBOs

The table contains results of investigation of trading during positive and non-positive NBBOs. Panels A and D contain market shares of participating venues calculated across the entire inter-market, similar to those in Table 1 (the shares sum up to 100% horizontally). Panels B and E contain statistics on trading frequency (calculated as the number of trades executed during each of the three NBBO types in a particular stock on a particular day divided by the number of minutes these NBBO types are active for a particular stock on a particular day); and Panels C and F contain average trade sizes (in shares). Differences in market shares in Panels A and D as well as differences in trade sizes in Panels C and F are tested for statistical significance with paired t tests. Superscripts † (‡) indicate that the difference between the current and the vertically adjacent (the one following the vertically adjacent) figures is insignificant.

	All	NASDAQ	Pacific (ArcaEx)	National (Island)	ADF (Instinet)	Chicago	AMEX
Panel A: NASDAQ, Market share, % of all trades							
Positive		36.18	28.73‡	25.12†	9.66†‡	0.28†	0.03†‡
Zero		38.40	25.73	24.86	10.77†	0.21	0.03†
Negative		40.51	27.47	21.83	10.01	0.14	0.04
Panel B: NASDAQ, Trading frequency, trades per minute							
Positive	9	12	9	8	3	<1	<1
Zero	15	22	15	12	6	<1	<1
Negative	57	87	48	40	20	9	1
Panel C: NASDAQ, Average trade size, shares							
Positive	395	538	351	298	281†‡	1,410	1,592
Zero	371	474	341	291	284	1,106	694
Negative	322	366	328	283	279	683	631

	All	NYSE	NASDAQ	Pacific	National	Chicago	Boston	Philadelphia
Panel D: NYSE, Market share, % of all trades								
Positive		67.37	18.03	2.58	2.33†	2.91†	6.11‡	0.67
Zero		52.29†	24.52	9.38	2.43	3.12	7.45	0.81
Negative		52.66	21.62	14.09	1.82	3.23	5.91	0.67
Panel E: NYSE, Trading frequency, trades per minute								
Positive	5	6	2	<1	<1	<1	1	<1
Zero	7	8	3	2	<1	<1	1	<1
Negative	9	11	6	7	1	2	2	1
Panel F: NYSE, Average trade size, shares								
Positive	1,102	1,408	651	307	482‡	928	462	1,376
Zero	1,326	1,644	579	254†	541	1,186	568	825
Negative	2,057	2,539	523	246	491	1,102	581	845

Table 11
Market quality
The table investigates market quality during different NBBO types. Due to inability of conventional trade classification algorithms to provide reliable results during the periods of non-positive spreads, we rely on the less involved methods of market quality measurement such as calculating shares of trade prices relative to the concurrent NBBO quotations. In particular, for different NBBO spread types we calculate the shares of trades executed at midpoint; at the concurrent NBBO ask; at the concurrent NBBO bid; inside the NBBO quotes, but not at the midpoint; and outside the NBBO quotes. We also measure the average distance between the execution price and the NBBO midpoint and the nearest quote. All distances from the midpoint and the nearest quote are significantly different across NBBO types, with the distances from the nearest quote for positive and zero NBBOs on NASDAQ being the only exception (identified with †).

	Execution relative to best quotes (%)					Distance from ($)	
	At midpoint	Inside	At ask	At bid	Outside	Midpoint	Nearest quote
Panel A: NASDAQ							
Positive	4.61	19.82	34.73	33.11	7.73	0.011	0.005†
Zero	76.96	—	—	—	23.04	0.005	0.005
Negative	0.96	6.42	23.99	25.34	43.29	0.024	0.009
Panel B: NYSE							
Positive	8.78	21.59	33.57	29.64	6.42	0.008	0.004
Zero	59.22	—	—	—	40.78	0.006	0.006
Negative	0.84	3.91	21.36	24.52	49.37	0.016	0.008

NYSE inter-market, therefore trades are not executed against smaller orders to resolve non-positive NBBOs.

5.4. *Market quality*

To close the discussion of trading during non-positive NBBOs, we investigate market quality. We refrain from using conventional measures such as effective and realized spreads, because their estimation relies on distinguishing buyer-initiated from seller-initiated trades by means of algorithms such as Lee and Ready (1991) or Ellis et al. (2000). We suggest that both of these algorithms may fail when the NBBOs become non-positive. According to the Lee and Ready algorithm, if a trade price is above (below) the NBBO bid (ask), but is below (above) the NBBO midpoint, the trade is classified as a customer sell (buy). During the locked markets, however, NBBO asks, bids, and midpoints converge into a single price, and the Lee and Ready algorithm breaks down. Ellis et al. augment Lee and Ready's procedure, using past prices to identify the direction of the trade. We argue that since locked and crossed markets are often caused by intensive price changes that are already occurring, price effects expected by the procedure may be overpowered and the algorithm may malfunction. The problems should only intensify in the case of negative spreads.

Due to the issues mentioned above, we turn to the less sophisticated measures of market quality that do not rely on the trade direction indicators. Specifically, we compute (i) shares of executions according to the price location with respect to the corresponding NBBO, (ii) distances between prices and NBBO midpoints and (iii) distances between prices and the nearest NBBO quotes. The results in Table 11 show that the distances between trade prices and midpoints as well as trade prices and the nearest quotes are the largest during negative spreads and the smallest during zero spreads. We also find that when the NBBO spreads are positive, 7.73% and 6.42% of all trades happen outside the NBBO, respectively, on NASDAQ and the NYSE. The shares of outside executions increase and diverge quite dramatically when the NBBO becomes zero. The difference becomes smaller when the inside spread is negative. Overall, the shares of outside-the-NBBO executions increase when the NBBO spread becomes zero or negative. This finding is attributable to the fact that locked and crossed markets tend to accompany informational events that cause uncertainty about future prices and, as a consequence, relatively high trading costs.

6. Determinants of non-positive NBBO initiations

As we suggest in the previous sections, there are several factors that may cause locked and crossed NBBOs. It is therefore necessary to verify whether our hypotheses hold in a multivariate regression setting. We use several logistic regression models with the dependent variables equal to 1 if the NBBO is locked or crossed by an offer quote and zero otherwise.[21] The models incorporate several regressors that include the NBBO immediately prior to the lock or cross, *lag_NBBO*; the time outstanding of locked (crossed) quotes on each of the sample markets, *locked_time_out*; the fact that the locked quote is an autoquote, *locked_auto*; the magnitude of the price change in the [-3; 0]-minute interval preceding the lock (cross), ΔP; and eight dummy variables for the time of the day.[22] The models accounts for fixed effects and non-spherical errors by allowing for clustering across stocks and by employing the Huber-White estimator for standard errors.

We expect narrow NBBOs to increase the probability of locks and crosses, as tight spreads may be indicative of high inter-market volume and high demand for speedy executions. Regression results in Table 12 confirm our expectations, as the coefficients on *lag_NBBO* are negative, indicating that wider NBBOs decrease the likelihood of locks and crosses.

According to the outdated quote argument, if a quote posted by a non-responsive venue becomes stale, market makers are likely to lock or cross this quote, if they find trading against it problematic. We thus expect the *locked_time_out* variable to have a positive influence on the probability of a lock (cross) on exchanges that are often tardy with quote updates and executions. Table 12 shows that such markets are AMEX and Chicago for the NASDAQ sub-sample, and Boston, National, Chicago, and Philadelphia for the NYSE-listed stocks. Generally, the signs of the coefficients are as expected for all market centers.

We also control for autoquotes, as they often appear on the locked side of the NBBOs in the NASDAQ inter-market as shown in Table 5. Coefficients for the *lock_auto* variables in the regression models for the NASDAQ sub-sample are positive and significant as expected, indicating that an autoquote has higher chances of being locked (crossed) than a quote for more than 100 shares. In the NYSE inter-market, however, the autoquote dummies are not significant in both specifications, corroborating our univariate findings.

[21]Regression results for the bid-initiated locks are consistent with the hypotheses developed throughout the paper and are not reported.

[22]Time-of-the-day dummy variables are used to control for intraday volume effects. As mentioned earlier, the number of locked and crossed NBBOs has a U-shaped intraday pattern similar to that of volume during the trading day.

Table 12
Determinants of zero and negative spread initiations

The table contains estimated coefficients of logistic regressions with dependent variables equal to 1, if non-positive spreads are originated by ask quotes. The following regressors are used: NBBO spread prior to the lock (cross), *lag_NBBO*; quote's time outstanding before locked (crossed), *locked_time_out*; locked (crossed) autoquote, *locked_auto*; and magnitude of price change in the 3-min interval prior to lock (cross), ΔP. The models control for intraday volume-related effects, fixed effects, and non-spherical errors. The global null hypothesis is tested with the Wald test. Goodman-Kruskal γ is used as a quasi-fit measure. Superscripts ***, **, and * denote, respectively, significance at 0.01, 0.05, and 0.10 levels.

	NASDAQ		NYSE	
	Lock	Cross	Lock	Cross
lag_NBBO	−3.108***	−2.907***	−4.582***	−0.854**
	(0.000)	(0.000)	(0.000)	(0.037)
Locked_time_out				
NYSE			−26.692***	−12.967***
			(0.000)	(0.000)
NASDAQ	−0.489*	−6.533**	0.328	2.092*
	(0.078)	(0.026)	(0.126)	(0.063)
Pacific (ArcaEx)	−9.446***	−7.289***	0.271	0.894**
	(0.000)	(0.000)	(0.319)	(0.037)
National (Island)	−2.359***	−5.828***	0.207***	0.538***
	(0.000)	(0.000)	(0.000)	(0.000)
ADF (Instinet)	−0.716***	−4.528***		
	(0.000)	(0.000)		
Chicago	0.016***	0.341**	0.309***	0.165*
	(0.005)	(0.042)	(0.000)	(0.054)
AMEX	0.264***	2.213***		
	(0.000)	(0.000)		
Boston			0.412***	0.527*
			(0.000)	(0.063)
Philadelphia			0.562**	0.139***
			(0.049)	(0.000)
Locked_auto	0.247***	0.068***	0.002	0.020
	(0.000)	(0.000)	(0.538)	(0.291)
ΔP	−0.039***	−0.014***	−0.229***	−0.193***
	(0.000)	(0.000)	(0.004)	(0.008)
Wald's Pr > $\chi 2$	0.000	0.000	0.000	0.000
Goodman-Kruskal γ	0.675	0.801	0.739	0.850

The price change variable, ΔP, is constructed as a sum of price shifts during the [-3; 0]-min interval preceding a lock (cross).[23] If the price is falling, the variable is negative, and the more intensive the price change, the larger the absolute value of the variable. An ask-initiated lock is more likely to occur when the price is falling, as the sellers who wish to sell promptly may refrain from sending their orders out, concerned that prices will fall further

[23]As results in Table 2 indicate that an average length of a positive NBBO for the NASDAQ sub-sample is 68.76 s, our use of 180-s (3-min) intervals to determine price changes may seem unwise. Unfortunately, when we re-run the models for [-1, 0]-minute intervals, the coefficients on ΔP are mostly insignificant, as the variable does not pick up much price variation. In the NYSE sub-sample, an average positive NBBO lasts much longer than that on NASDAQ, namely 532.15 s, therefore we decide to present intervals of [-3, 0] min to preserve consistency between the sub-samples and assure statistical significance of the results.

Table 13
Determinants of zero spreads initiated by ECNs: NASDAQ sub-sample

The table contains results of Tobit regression models estimated for each ECN individually. We only consider the 100 NASDAQ-listed stocks, because the ECNs are not as active on the NYSE as they are on NASDAQ. Quantities of market, marketable limit, inside limit, at the quote limit, outside limit orders, and shares executed away from the ECNs, *sh_away*, are obtained from the Dash-5 datasets. Island did not accept market orders during our sample period. Number of zero spread initiations by an ECN (censored dependent variable) and average time outstanding of the quotes on the opposite side of the locked NBBO, *locked_time_out*, are obtained from the TAQ. *p-values* for the heteroskedasticity-robust standard errors are provided in parentheses. The models control for fixed effect by allowing for clustering across sample stocks. Intercepts are not tabulated to preserve space. Superscripts ***, **, and * denote, respectively, significance at 0.01, 0.05, and 0.10 levels.

	Pacific (ArcaEx)	National (Island)	ADF (Instinet)
Number of			
Market orders	−0.094	N/A	0.391
	(0.382)		(0.292)
Limit orders			
Marketable	0.072***	0.047***	0.044***
	(0.000)	(0.000)	(0.000)
Inside	0.074	−0.012***	−0.071***
	(0.123)	(0.000)	(0.000)
At the quote	−0.011**	−0.002	0.003
	(0.026)	(0.105)	(0.292)
Outside	0.000	0.000	0.000
	(0.416)	(0.349)	(0.256)
sh_away	0.097***	N/A	0.058***
	(0.000)		(0.000)
locked_time_out			
NASDAQ	2.158***	−0.003	2.639**
	(0.000)	(0.147)	(0.045)
ArcaEx		0.412	−10.993***
		(0.183)	(0.000)
Island	−4.015***		−8.922***
	(0.000)		(0.000)
Instinet	−12.003***	−0.007	
	(0.000)	(0.691)	
Chicago	0.081	0.034**	0.069**
	(0.758)	(0.041)	(0.042)
AMEX	0.015***	0.024**	0.030***
	(0.000)	(0.012)	(0.000)
$R^2_{\text{ANOVA}} = \sigma^2_{\hat{y}} / \sigma^2_{y}$	1.512	0.875	0.769
$R^2_{\text{DECOMPOSITION}} = \sigma^2_{\hat{y}} / \left(\sigma^2_{\hat{y}} + \sigma^2_{\varepsilon}\right)$	1.067	0.817	0.637

while the orders are in transit. We therefore expect the coefficient for ΔP to be negative, since a negative price change multiplied by the negative coefficient gives a higher probability of a lock (cross) by an ask quote. Regression results for both inter-markets confirm this conjecture.

The inaccessibility, stale quote, autoquote, and order-in-transit considerations discussed above may lead to both zero and negative spreads. Negative spreads are, however, not economically feasible from the rebate-seeking standpoint. Since a reward for submitting a marketable limit order is usually only a couple of millicents, crossing a quote and losing at least one cent on a transaction against this quote does not seem to be a profitable strategy. This argument is supported by the results of the Goodman-Kruskal (G-K) test in Table 12. The G-K γ, which is a measure of the association of predicted probabilities and observed responses (or a quasi-fit measure), is higher for models of crosses than those of locks. This result suggests that the models for locks are missing an important regressor, possibly the one that accounts for rebate-seeking orders coming from the ECNs. Note that the difference in γs between models of locks and crosses is smaller on the NYSE, which is most likely due to the lack of the ECN activity on this inter-market.

It is, unfortunately, impossible to explore the influence of rebate-seeking marketable limit orders on locked NBBOs with the TAQ trade-by-trade data. Hence, we refer to the Dash-5 datasets to determine whether the number of marketable limit orders increases the quantity of non-positive spreads originated by the ECNs. Three Tobit models are used, as shown in Table 13, to investigate the relationship between the *number of zero spreads* originated by the three identifiable ECNs and the number of *market*, *marketable limit*, *inside limit*, *at the quote limit*, *outside limit orders* submitted to these ECNs and two controls: shares executed away, *sh_away*, and an average outstanding time of locked quotes, *locked_time_out*. Since the data in the regressions are pooled, we control for fixed effects across stocks and for heteroskedasticity.

The only order type variable that we expect to positively affect the number of lock initiations is the quantity of marketable limit orders submitted to each ECN. Since the other order types are not likely to lock the market, we expect their coefficients to be close to zero or, possibly, negative, if submission of these orders is negatively correlated with submission of marketable limit orders. The *sh_away* variable allows us to inquire whether, for a particular stock, the number of orders routed away from the ECNs affects the number of zero NBBOs initiated by the ECN. We expect this variable to have a positive coefficient, as stocks with lower ECN liquidity should be more susceptible to locks originated out of concern of losing a price while an order is in transit. The *locked_time_out* control is expected to have coefficients with signs similar to those presented in Table 12.

The results of the Tobit models are provided in Table 13 and, generally, support the rebate hypothesis, as the only order type that consistently positively affects the number of locks is marketable limit orders. We acknowledge that this order type may also originate the locks covered by the order-in-transit hypothesis; however, we believe that, by including the *sh_away* regressor in the model, we at least partially control for the order-in-transit argument (*sh_away* variable is not available for Island in the Dash-5 data set). Finally, the coefficients for the *locked_time_out* control variable exhibit expected signs for most of the sample venues. Moreover, all but a few coefficients are statistically significant, leading us to conclude that, even in the aggregate setting of the Dash-5 data, our hypotheses continue to hold.

7. Conclusion

This study finds that the NASDAQ inter-market is locked or crossed about 10% of the time, with all of the NASDAQ sample stocks affected by non-positive spreads. The locked and crossed NBBOs are not as abundant on the NYSE inter-market, but still account for about 4% of the trading time. Zero and negative spread periods are frequent but fleeting events and are usually resolved within 30 s of origination. Trading intensifies and market quality deteriorates during non-positive spreads. The decrease in market quality may be attributed to price changes that locks and crosses often accompany.

We discuss several possible causes of locked and crossed markets. Initially, we inquire whether originations of zero and negative spreads can be explained by the lack of coordination among market centers in today's fragmented trading environment. We find evidence to support this argument, based on the fact that a significant share of non-positive spreads is due to quotes posted simultaneously or within two consecutive seconds. We also address connectivity problems between AMEX and SuperMontage that often result in NASDAQ dealers ignoring electronically unreachable quotes posted by AMEX. Another cause of non-positive NBBOs confirmed by this study is stale and autoquotes that are often avoided by traders seeking speedy and certain executions. Yet another cause of non-positive spreads is related to order transit considerations in a multi-market setting. We hypothesize that, at times, traders may not be willing to send time-sensitive orders to markets with the best quotes, because these traders' information may lose its value while the order is in transit. Such traders may find locking or crossing the NBBO to be a suitable way to attract liquidity. Finally, we show that zero spreads may be caused by rebate-seeking traders that submit marketable limit orders to the ECNs.

The recently adopted Regulation NMS urges market participants to avoid creating non-positive spreads. The Commission suggests that locked and crossed NBBOs are "inconsistent with orderly markets" and "create confusion for investors." The Regulation suggests that only automatic quotes be allowed to lock manual quotes and that manual quotes should not be allowed to lock automatic quotes. This proposition seems rather discordant with the main arguments of this study. In particular, inaccessible AMEX quotes are likely to be automatic and, according to the Regulation, would not be allowed to be locked. Auto-quotes posted by tardy market centers are also likely to be automatic, again, prohibiting market participants from locking and crossing them. As to NBBOs locked (crossed) due to order-in-transit considerations, it may be argued that making it more difficult for informed traders to execute time-sensitive orders may impair price discovery. The issue of ECN liquidity and rebates is a complicated one; however, we suggest that the pros of decreasing the number of locked markets need to be weighted against the cons of weakened ECN liquidity, price discovery, and execution speed. We conclude that, although non-positive NBBO periods often disrupt electronic executions and irritate market makers and SEC regulators, they should be viewed as natural phenomena in fast-moving segmented markets.

A series of mergers in US securities markets has changed and continues to change the competitive landscape of securities trading. The merger of Island and Instinet and the more recent mergers of NASDAQ and INET as well as the NYSE and ArcaEx may well decrease fragmentation and reduce the quantity and frequency of non-positive NBBOs. We believe that despite these recent events, understanding the origins and consequences of locked and crossed markets is important in the ever-changing world of securities trading.

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