Locked and Crossed Markets on NASDAQ and the NYSE

Andriy V. Shkilko, Bonnie F. Van Ness, and Robert A. Van Ness*

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Abstract

NBBO for an average stock is locked or crossed 10% and 3.5% of the time on, respectively, NASDAQ and the NYSE inter-markets. Locks and crosses usually accompany significant price changes. We show that non-positive spreads arise because of (i) occasional invisibility of quotes or tardiness with stale quote updates, (ii) price/time priority considerations, and (iii) ECN liquidity-attraction practices. We suggest that although Regulation NMS, recently approved by the SEC, urges market participants to avoid locking and crossing the consolidated quotes, the non-positive spreads often represent examples of natural competitive behavior in contemporary fragmented markets.

1. Introduction

Security markets frequently undergo structural and regulatory changes. Such changes usually benefit both trading and investment communities by increasing transparency, accelerating executions, enhancing liquidity, and ensuring better price support. Nonetheless, at times, the pace and magnitude of innovations may appear overwhelming even for a well-tuned trading mechanism and may lead to disruptions and other disturbances to the exchange process. In recent years, market makers involved in the trading of the NYSE- and NASDAQ-listed securities have faced two challenges: tick size reduction and expansion of alternative trading platforms such as electronic communication networks (ECNs). These two innovations have significantly altered the way markets operate and have drastically changed the competitive landscape.

Tick size reductions and their consequences are the focus of a number of academic studies. Bessembinder (1999) compares trading costs on the NYSE and NASDAQ and finds that executions become cheaper following the switch to sixteenth on both markets. In contrast, Jones and Lipson (2001) show that execution costs do not significantly change for small orders and even increase for large orders when measured directly instead of through spread proxies. Werner (2005) finds no evidence of deteriorating execution quality after decimalization. We augment this area of research by suggesting that, aside from execution quality, tick size reductions are likely to have an impact on market participants' quoting habits. In particular, decimalization makes it easy (by simply altering quotes by as little as one cent) to jump in front of other orders and realize the benefits of price/time priority. Combined with a pervasive decrease in spreads to, at times, just one cent; such jumping practices are likely to lock or cross the NBBO.

Another dynamic relevant to our discussion is the explosive proliferation of ECNs, especially in the market for NASDAQ stocks. Goldstein et al. (2005a) show that the NASDAQ Stock Market executes only 51.59% of all trades in affiliated securities; while the three major ECNs: Island, Instinet, and ArcaEx – capture as much as 47.73% of trade flow. In another study, Goldstein et al. (2005b) investigate the competitive structure of the NYSE inter-market and find that trading appears to be more concentrated on the leading market center, the NYSE, which executes 64.62% of orders. The authors conclude that a combination of factors such as decreased tick size and expansion of alternative trading platforms leads to greater competition for order flow and substantially reduces traders' costs in both inter-markets. On NASDAQ, however, the aforementioned factors not only cause market quality to improve, but also lead to propagation of locked and crossed NBBOs. In particular, Goldstein et al. find that 14.67% of NASDAQ's NBBO spreads are non-positive.

A market is considered to be locked (crossed) when the inside ask is equal to (is less than) the inside bid, which makes the NBBO spread equal to (less than) zero. Existence of non-positive NBBOs may seem to run counter to Demsetz's (1968) notion that the spread represents a payment for the opportunity to trade immediately. In addition, locked and crossed markets may also seem to be inconsistent with the models that assume that spreads are remunerations for asymmetric information, inventory, and order processing costs (e.g., Glosten and Harris, 1988; Lin, Sanger, and Booth, 1995; and Huang and Stoll, 1997). The aforementioned theoretical models, however, refer to the spreads of a single market maker rather than those comprised of quotes from different venues. In today's trading environment, while one market's offer is usually higher than its bid, it may be equal to (less than) a bid posted by a different market. This situation does not contradict the aforementioned spread theories, since market makers on both venues are still likely to receive compensation for the incurred costs.

Although locked and crossed markets do not directly interfere with the market makers' ability to cover trading expenses, their instances are often detested by traders and regulators. The SEC's recently adopted Regulation NMS, for instance, recommends that market participants reasonably avoid creating non-positive spreads, because "locks and crosses are inconsistent with fair and orderly markets and detract from market efficiency." The commission also blames zero and negative spreads for creating confusion for investors as it "becomes unclear what the true interest in the stock is." The Regulation proposes to only allow locking of manual quotes by automatic quotes and to disallow locking of automatic quotes by manual quotes. This study suggests that although non-positive spreads may seem unnatural, they represent the markets' evolutionary adjustment to the existing trading environment. We suggest that locked and crossed NBBOs are caused by (i) electronic inaccessibility of certain quotes and markets' sluggishness with quote updates, (ii) competition for price/time priority in a multi-venue setting, and (iii) liquidity rebates issued by ECNs and Island's rejection of market orders.

From an academic prospective, analysis of locks and crosses is important because a number of empirical studies treat non-positive spreads as insignificant mechanical phenomena 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 NBBO spread is non-positive. For our sample, transactions eliminated in this fashion would comprise 5.17% of the NYSE trades and 22.19% of NASDAQ trades, which may be inconsistent with unbiased sample selection. Although the number of locked and crossed markets as well as their frequency is alarming, several recent papers (e.g., Boehmer, 2005; Lipson, 2005; and Werner, 2005) that examine execution quality in a competitive market setting completely ignore this issue.

Currently, only two studies analyze instances of non-positive spreads. Cao, Ghysels, and Hatheway (2000) show that, due to the absence of trading during the pre-opening session, informed NASDAQ dealers use locks and crosses to show their less informed colleagues the direction in which the price is moving. In their sample of the 50 most active NASDAQ-listed stocks in October 1995 through September 1996, 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. Instances of non-positive spreads are also documented for the exchange-listed options markets: Battalio, Hatch, and Jennings (2004) find that the amount of time that actively traded options spent in locked and crossed markets decreases between June 2000 and January 2002. They attribute this decline to the options markets' becoming more efficient at the end of the sample period, after the SEC's approval of a plan to impose more stringent quoting and disclosure rules on the options trading.

We assert that extant academic literature lacks empirical evidence on non-positive spread episodes that occur on the major stock markets 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 testing several hypotheses of their origination. In addition, we challenge the conventional perception of non-positive spreads as detrimental occurrences. Although trades are shown to execute further from the midpoints when the NBBO is crossed, we do not find this evidence sufficient to claim deterioration of market quality. Conversely, we view non-positive spreads as a natural mechanism that allows traders to cope with today's increasingly competitive and fragmented market environment.

The rest of the paper is organized as follows. Section 2 suggests several reasons for non-positive spread origination. Section 3 describes the sample. Section 4 provides evidence on initiators, victims, and terminators of locked and crossed markets, as well as the length and frequency of the latter. Section 5 investigates trading activity and market quality during the non-positive NBBOs. Section 6 tests the hypotheses of zero and negative spread initiation. Section 7 concludes.

2. Hypotheses

Both the NASD and the SEC regulators are aware of the phenomenon of locked and crossed markets.[1] In fact, Regulation NMS is, in part, an attempt by the SEC to eliminate the non-positive NBBOs. Dealers also find locked and crossed markets to be an ongoing problem. According to Ed Coughlin, head of NASDAQ trading at Madoff Investment Securities LLC, "It's confusion [and] it definitely affects price discovery.[2]"

There are several factors most often blamed for causing non-positive spreads. The first is faulty connectivity among market centers. Since both the NYSE and NASDAQ have multiple venues quoting their securities, quotations may, at times, be posted without proper coordination and lock or cross the market. This argument is consistent with that of Madhavan (1995) and Conrad, Johnson, and Wahal (2003) who mention that fragmentation may lead to price efficiency and disclosure violations. The point is also asserted by Sang Lell, a manager of the securities and investments group at Celent Communications who, when asked about non-positive spreads, claims that "the problem is […] multiple venues for trading NASDAQ stocks.[3]" Indeed, the multiplicity of quote and trade sources may become a serious impediment to efficient market operations. Suppose two exchanges 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 exchange are not aware of the quotes posted on the other exchange due to the invisibility of the latter, the NBBO spread may be unintentionally locked or crossed. Collectively, this viewpoint asserts that locked and crossed markets are the result of poor coordination and/or quote inaccessibility among market centers and are, mostly, unintentional.

Our findings support this notion only to a certain extent. First, we show that, in the inter-market setting, non-positive spreads that result from simultaneous posting of locking or crossing quotes are rather rare and do not exceed 1% of all locked and crossed instances. Second, the data do not contain a significant number of instances when a locking (crossing) quote and a locked

[1] "Results on the Introduction of NASDAQ's SuperMontage," by NASDAQ Economic Research.
[2] "NASDAQ's battle over locked and crossed markets," Wall Street and Technology Online, April 15, 2003.
[3] Ibid.

(crossed) quote are posted within several seconds of each other: the average time a quote is outstanding before it is actively locked is more than 40 seconds, while the mean time a quote is outstanding before is it crossed is more than 15 seconds. Taking into account current levels of computerization, we do not find it feasible that it takes more than a few seconds for a newly posted quote to be observed and acknowledged by others in the market. The only exception to this standard that we are aware of is the connectivity problem between AMEX and the SuperMontage. During our sample period, AMEX quotes are electronically unreachable, so the SuperMontage participants often tend to ignore them, causing locks and crosses.

As shown by Cao, Ghysels, and Hatheway (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 argue that, in the absence of trading, non-positive spreads are an effective method of price discovery. Our analysis does not concentrate on pre-opening sessions, but rather on the trading day, during which price movements can be observed by all participants, and better informed market makers may trade against outdated quotes instead of locking or crossing them. We hypothesize, however, that, in certain cases, execution of such trades may not be plausible from the active market participant's standpoint. For instance, a stale quote may be posted by a slower market, on which execution may take an unreasonably long period of time; or it may be an auto-quote for only one hundred shares. Alternatively, the market maker with an obsolete quote may be non-responsive, making an informed trader with time-sensitive information ignore the stale quote and lock or cross it. Collectively, according to this view, non-positive spreads arise when executions against outdated quotes are problematic due to the posting market's immobility, irresponsiveness, or inadequate depth.

Our findings are, generally, consistent with this hypothesis. We find that, for NASDAQ stocks, quotes posted by AMEX and Chicago are usually locked after having been outstanding for more than nine minutes. A similar pattern emerges for the NYSE listings: Boston, National, Chicago, and Philadelphia Stock exchanges have their quotes locked after having been posted for more than seven minutes. Accounting for the fast pace of price changes in contemporary markets and for the finer decimalized price grid, it is reasonable to believe that a seven-minute-old quote may not reflect the latest price updates and may be regarded as inadequate by traders on more active market centers. Indeed, tests of price change intensity reveal that locked and crossed markets tend to occur during the most potent price shifts, during which timing of trades is very important for investors, and execution delays may appear detrimental to their trading strategies. In addition, regression results show that, on AMEX and Chicago for NASDAQ stocks and on Boston, National, Chicago, and Philadelphia for the NYSE issues, the quote's age increases the probability of a lock (cross). For other venues, however, the age of quotes either does not affect or prevents non-positive spreads. According to the stale quote reasoning, outdated quotes are only locked if it is difficult to execute against them. Apparently, market participants often find it problematic to trade against the outdated quotes posted by the markets mentioned above, whereas other exchanges are more responsive and therefore are able to avoid being locked and crossed.

Multi-market trading, at times, causes undesirable degrees of order flow fragmentation that, in turn, may lead to complications for investors concerned about timeliness of executions. Suppose market A is currently quoting the best bid, and there is a notable number of customer market sell orders pending to be executed against this bid. Suppose further that market B does not quote the best bid, but there is a trader on this market who is willing to sell at the current NBBO bid. One way for this trader to transact is to communicate his order to exchange A and wait for execution according to the time priority. Alternatively, the trader may post a locking offer quote (submit a marketable sell limit order) on (to) market B and establish price/time priority on this market. A reasonable trader would often choose this strategy, since the cost of posting a locking quote (submitting a marketable limit order) is minimal (lower than that of a market order). In a similar fashion, a market maker may be reluctant to send an order to another venue with a better quote, because it may often be the case that, while the order is in transit, the other venue's quotes change, and the order is returned to the original market maker unfilled. A less costly approach from the trader's perspective is to ignore the other market's quotes and alter his own, leading to a locked market. Collectively, due to timing issues and uncertainty about fulfillment, traders may not always be willing to send orders to the markets with best quotes, but rather post their orders locally, leading to locked or crossed NBBOs.

Since we do not possess data on individual decision making and can only observe orders *ex post* execution, we employ several proxies for trading intensity to test the time/price priority argument. In particular, we use several regressors that are conjectured to be correlated with the probability of a queue formation on the market with the best quotes, market A. If there is such a queue on the venue that is currently quoting the best bid, there is a possibility that traders on market B will refrain from sending their time-sensitive trades to A and will lock the NBBO instead.

Regression results generally support our logic, as the logistic procedure delivers expected signs for factors that are hypothesized to cause non-positive spreads according to the price/time priority argument.

Yet another cause of zero spreads is related to access fees on the ECNs and NASDAQ. The networks, being software-operated trading mechanisms, do not employ professional market makers able to maintain inventory in a stock and provide sufficient liquidity. This factor makes ECNs prone to liquidity shortages, forcing them to employ various techniques of attracting liquidity-providing orders (Hansch, 2004, Hasbrouck and Saar, 2004). One of these techniques involves a partial refund of access fees to liquidity providers – traders who submit limit rather than market orders. Limit orders submitted to most of the ECNs and, sometimes, NASDAQ are typically rewarded with a 2 mils (millicents) per share rebate of a standard 3 mils non-subscriber access fee; while liquidity consuming market orders are charged the entire fee. Due to these rebates, ECNs and NASDAQ clients who are willing to trade at an outstanding market price often post marketable limit orders with a desired sell (buy) price equal to that of the NBBO bid (ask). Upon posting, these sell (buy) orders change the NBBO quotes by lowering the offer (raising bid) to a point where bid and offer prices become identical, and the NBBO locks.

Not all ECNs accept market orders: Island, for instance, only allows traders to submit limit orders. If a market participant on Island is looking to buy (sell) at an outstanding NBBO price and wishes to execute in a timely manner, she is likely to submit a marketable limit order with the limit price equal to the sell (buy) side of the NBBO and, consequently, lock the market. While previous research examines the execution quality of marketable limit orders (e.g., Angel, 1997, Harris and Hasbrouck, 1996, and Peterson and Sirri, 2002); their effect on locked markets remains unreconciled in the current literature. Collectively, this view holds that zero spreads on NASDAQ are initiated by rebate- or (on Island) fast execution-seeking ECN traders who post marketable limit orders.

We show that ECNs frequently initiate non-positive spreads and are often the ones to unlock the market after initiating a lock. The latter finding can be attributed to the fact that quotes produced by the marketable limit orders are withdrawn as soon as these orders are executed. Lastly, the outcome of Tobit regressions indicates that marketable limit orders are the only order type that positively and significantly influences the number of zero spread initiations 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-listed stocks in November 2003.[4] The data are obtained from the TAQ database provided by the NYSE. For the NASDAQ-listed sub-sample, we use data for the entire trading day, from 9:30 a.m. to 4:00 p.m., EST; while for the NYSE-listed securities, the first fifteen minutes of trading on each day are omitted to exclude possible effects of a call auction. Quantities of market, marketable limit, inside limit, at the quote limit, and outside limit orders submitted to the ECNs are obtained from Transaction Auditing Group, Inc. and Instinet Group, Inc.

During the sample period, trading and quoting of 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 Stock Market.[5] In the past several years, an increase in competition for order flow for NASDAQ-listed securities made the TAQ data more informative about the inter-market's structural landscape and allowed for sufficiently accurate identification of the leading competitors. Goldstein et al. (2005) show that, from April until December of 2003, the three major ECNs: Island, Instinet, and Archipelago dominate on, respectively, the National Stock Exchange, 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-listed sub-sample.[6]

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 Stock Market, and the Philadelphia Stock Exchange. Goldstein et al. (2005b) find that ECNs are not as active in the NYSE inter-market as they are in the market for the NASDAQ listings, and that the networks' activity cannot be

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[4] We define the most actively traded stocks as the ones with the highest trading volume during the sample month.

[5] The Cincinnati Stock Exchange changed its name to the National Stock Exchange on November 7, 2003. Since the larger segment of our calendar sample occurs after the change, we choose to refer to the venue according to its newly acquired name.

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

easily separated in the data from that of the hosting market venues. For this reason, we do not identify the ECNs for the NYSE-listed sub-sample.

Table 1 provides sample summary statistics with results for the NASDAQ-listed sub-sample are presented in Panel A. Our findings indicate that quoting and trading differ drastically between the two inter-markets. For instance, ArcaEx appears to be the most active quoting venue, whereas two other ECNs participate in quoting less intensively. Overall, the networks originate 67.9% of quotations. High ECN activity confirms earlier results of Huang (2002) and Goldstein et al. (2004a) who suggest that the networks post more quotes, because orders routed to ECNs execute against the outstanding market or limit orders at the inside of the venue's order book. If such a transaction consumes the entire inside depth, the ECN quote changes to reflect the next layer of limit orders, and the new quote is posted. Meanwhile, the dealer/specialist exchanges change their quotes less frequently after trade executions, since their quotations are not as directly related to the limit order reserves as those of the ECNs. In particular, AMEX and Chicago appear to have the lowest shares of quotes, while NASDAQ is only second in quoting of its own securities, originating 28.16% of quotes, but has the largest trading share with as much as 36.38% of all executions.

Although both AMEX and Chicago rarely participate in trading, their mean trade sizes appear almost three times as large as those on NASDAQ and up to five times as large as those on the ECNs. Goldstein et al. (2004a) surmise that orders routed to the AMEX and Chicago exchanges are predominantly institutional and may result from preferencing agreements between several large investors and market makers on the two exchanges.[7] Consistent with the extant empirical findings, we also find that ECN-hosting exchanges have comparatively small average trade sizes. A possible reason for the ECNs' reporting of the smaller trade sizes is twofold: first, it may be due to the fact 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 orders of a lesser size are likely to be broken up and reported as smaller trades.

Panel B of Table 1 provides the results for the NYSE-listed sub-sample. We observe that the NYSE possesses the highest share of quotes and trades. The Pacific Stock Exchange is the next most active venue in terms of quote submission, but its quoting activity does not translate into

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[7] During the sample period, AMEX and Chicago do not quote or trade all sample stocks. The Chicago Stock Exchange always participates in trading of more stocks than it quotes, with the number of quoted stocks never exceeding the number of stocks with completed trades. This finding reinforces our belief in the existence of preferencing agreements between the Chicago market makers and certain investors. These arrangements allow the exchange to receive orders without posting quotes in a security but merely agreeing to match the existing quotes.

trading activity (26.75% of quotes compared to only 2.97% of trades).[8] Overall, our findings are consistent with Harris (2003) and Goldstein et al. (2004b) who find that ECNs are able to successfully compete for order flow on NASDAQ, but are not as successful on the NYSE.

According to the statistics provided in Table 1, the NYSE executes 66.85% of trades in the NYSE-listed stocks, while NASDAQ only completes 36.38% of the trades in the NASDAQ-listed securities. The lower trading share implies that the NASDAQ market is much more fragmented than the NYSE. As noted by Goldstein et al. (2004a), a relatively segmented trading system may be more prone to prolonged periods of locked and crossed markets – situations in which the NBBO offer prices appear equal to or lower than the bid prices. In the next section, we take a closer look at the non-positive NBBO periods in a cross-sectional setting, in particular, at their length as well as initiation and termination patterns.

4. Non-positive Spread Characteristics

We use quotes and relevant quote time stamps from each market center to reconstruct the national best bid and offer. The spreads that we reproduce frequently appear equal to or less than zero. Specifically, 15.16% of NBBOs in the NASDAQ inter-market (Table 2, Panel A) and 4.15% of NBBOs in the NYSE inter-market (Panel B) are non-positive.[9] We then conduct an F test to check whether the daily quantities of non-positive NBBO spreads are consistent throughout the sample month. The results (represented by the p-values) indicate that the daily quantities of locked and crossed quotes do not vary significantly across the month of November on either market. Overall, more non-positive spreads occur on the more fragmented NASDAQ than on the more consolidated NYSE inter-market. If we believe that non-positive spread periods are detrimental to market quality, the abundance of zero spreads on NASDAQ adds to the argument of Amihud, Lauterbach, and Mendelson (2003) who argue that consolidated markets benefit from better liquidity and pricing; as well as reinforces the evidence of Bennett and Wei (2003) who show that the NYSE provides better market quality than NASDAQ. On the other hand, as shown by Klock

[8] The abundance of quotes coming from the Pacific Stock Exchange as well as the fact that the venue executes trades of smaller sizes seem to be indicators of ECN activity. We hypothesize that ArcaEx is more active in market making in the NYSE-listed stocks than the other two major ECNs; however, due to the lack of factual evidence we refrain from attributing Pacific's activity to ArcaEx.

[9] We then subdivide non-positive spreads into zero and negative sub-categories. An average amount of zero spreads on NASDAQ appears to be slightly over 12%, while the amount is somewhat less than 3% on the NYSE inter-market. An examination of negative spreads reveals that 2.94% and 1.20% of, respectively, NASDAQ and the NYSE quotes are crossed.

and McCormick (1999), higher fragmentation of trading on NASDAQ due to existence of multiple dealers is correlated with lower spreads. According to this argument, zero spreads may be viewed as a result of greater within- and inter-market competition and as beneficial to traders.

Although the number of non-positive spreads in the two markets appears quite high, the issue may not be as momentous as it appears if the duration of zero and negative spread episodes is not sufficiently long. Table 2 shows the length of positive, zero, and negative NBBO episodes, for the NASDAQ (Panel A) and the NYSE (Panel B) sub-samples. The market for a NASDAQ stock is locked, on average, for 4.57 seconds and is crossed for 8.84 seconds; while the market for an NYSE-listed security is usually locked and crossed, respectively, for 6.51 and 25.15 seconds. Overall, these results indicate that quoting anomalies are resolved fairly quickly in both markets. A far more notable fact is the frequency with which these episodes occur. For instance, on NASDAQ inter-market an average stock is locked or crossed every 1.12 minutes, whereas on the NYSE – every 9.44 minutes. Although the situations are resolved quite promptly, the repeated disruptions of electronic executions may present an impediment to market efficiency, especially on NASDAQ.[10]

The fact that locked and crossed markets do not last particularly long causes the time-share of non-positive spreads to be lower than the share of instances. In terms of elapsed time, zero and negative spread episodes account for, respectively, 8.43% and 1.51% of an average trading day on NASDAQ, and 2.29% and 1.28% on the NYSE. The results on maximum time ranges of the non-positive spread episodes provided in Table 2 show that, in the NASDAQ sub-sample, each of the stocks is affected by locked or crossed markets: the longest uninterrupted trading period lasts for 2.40 hours (8,652 seconds).[11] On average, crossed markets last longer than locked markets on both exchanges. We conduct a paired *t* test for the difference in means between the NASDAQ and the NYSE time shares of negative spreads, which does not allow us to reject the hypothesis that these time shares are identical. This means that although NASDAQ and the NYSE are affected by locked markets to different degrees, crossed markets influence both equally, consistent with the notion that the majority of zero spreads on NASDAQ are caused by the ECN traders that are not very active on the NYSE. Crosses, on the other hand, are less likely to be caused by ECN order submission practices and are more often originated by market makers' not seeing or ignoring stale quotes.

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[10] Goldstein et al. (2005a) mention that when NBBO spread becomes non-positive, several types of trading software halt executions until the issue is resolved manually.

[11] The longest time period the market for one of the NASDAQ-listed securities was crossed, 5.93 hours (21,347 seconds), is a result of the PanAmSat Corporation's (SPOT) stock being crossed for most of the trading day on November 25th. In the meantime, on the NYSE, some of the sample stocks avoid locks and crosses.

It is important to differentiate between the two different ways the NBBO can be locked – active and passive. We consider a market to be actively locked when one exchange deliberately submits a(n) bid (ask) quote that is equal to the currently outstanding best ask (bid) quote maintained by another exchange. Conversely, a passive lock happens when a market for a security is coming out of a cross. If, while the market is crossed, an exchange submits a(n) bid (ask) quote that has a potential of locking the market (namely, is equal to an active inside ask (bid) quote on the other side of the NBBO), this quote stays dormant until the cross is resolved. If the cross is ended by one of the crossing exchanges' pulling out its quote, the passive quote may become active and, subsequently, lock the market. In case of crosses, a negative spread can arise only actively, when an exchange submits a(n) bid (ask) that is higher (lower) than existing best ask (bid).[12]

Non-positive spreads may also be differentiated according to implied intent; in particular, we distinguish between the intentional and unintentional locks (crosses). An intentional lock is a result of a posting of a(n) bid (ask) quote equal to an outstanding NBBO ask (bid) quote; and an intentional cross occurs after posting of a(n) bid (ask) quote that is higher (lower) than an outstanding ask (bid). Since market makers on the initiating venues are able to see outstanding NBBO quotes before they post locking or crossing ones, we refer to locks and crosses described above as *intentional*. *Unintentional* can be, in turn, divided into *simultaneous* and *passive*. Simultaneous lock (cross) is a result of two exchanges' concurrent posting of NBBO inside 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 show that simultaneous locks and crosses as well as un-locks and un-crosses are very rare and represent less than 1% of non-positive spread occurrences. The majority of locked and crossed markets are intentional, with only 7.06% and 3.47% of zero spreads on, respectively, NASDAQ and the NYSE initiated by passive locks; and only 0.70% and 0.51% of negative spreads are commenced by unintentional crosses. Since unintentional locks and crosses are merely a result of miscommunication among the market centers and represent a very small portion of the non-positive spread instances, we do not closely investigate them in the paper. Passive locks may seem to present more interest as they happen more

[12] Technically, a quote that may cause a cross may be submitted while the market is already crossed by a quote submitted earlier. Such a new quote (if still active) will keep the market crossed even if the original locking quote is withdrawn. We do not differentiate these cases of consecutive crosses from those where the market is crossed by only one quote as the number of such occasions is close to zero.

frequently; however, they usually happen during transitional periods between negative and positive NBBOs and have low informational content.

4.1. NASDAQ

On NASDAQ, the highest fraction of quotes that actively lock the market, 34.97%, is coming from the Archipelago ECN. Instinet and NASDAQ also enter a significant number of quotes that lead to non-positive NBBO spreads, respectively, 31.66% and 14.01% of locking and 25.40% and 20.91% of crossing quotes. NASDAQ is most often affected by non-positive spreads: it appears to be at the static side of the NBBO in 37.58% of locked and 29.42% of crossed instances. The other group of exchanges that often have their quotes locked consists of ArcaEx, Instinet, AMEX, and Island with shares of locks ranging from 17.95% to 11.35%. Chicago is less affected by either type of non-positive spreads, likely because the exchange rarely participates in the NBBO. As to the crossed quotes, the situation appears somewhat different. In this case, AMEX is on the static side of the NBBO in 27.07% of cases, which is quite surprising given the venue's relatively inactive quoting. The rest of the market centers suffer from crossing to a much lower degree than do NASDAQ and AMEX.

Neither the leading initiator of zero spreads – ArcaEx, nor the venue that is locked most often – NASDAQ, appear to dominate the recovery process, namely, that of ending locked markets. The most active venue in this case is Instinet, causing 27.61% of terminations. NASDAQ follows with a 26.65% share, and Archipelago is third most active, ending 22.15% of zero spreads. AMEX is also quite active in zero spreads terminations, ending 13.05% of them – a notable share for a less active market center. Even more impressive is AMEX's share in ending crosses – 30.40%. NASDAQ and ArcaEx are also quite active in ending crosses with, respectively, 26.30% and 21.71% shares.

It does not come as a surprise that the more active market centers that generate the majority of quotes also initiate a lot of non-positive spreads. Therefore, although instructive in terms of structural landscape, Panel A's results remain uninformative regarding the pace of non-positive spread initiations by each venue. Since ArcaEx submits more quotes than the other market centers, it is more likely to be responsible for a larger number of locking and crossing quotes, even if a ratio of locking and crossing quotes to non-locking and non-crossing ones is the same as that on, for example, AMEX. To elaborate on this argument, we calculate fractions of lock- and cross-initiating quotes in all NBBO-forming quotes submitted by each of the sample exchanges (Panel B of Table 4). Our statistics reveal that the differences between initiations of zero spreads by different venues are quite subtle, with the share of lock-causing quotes ranging from 0.39% on NASDAQ to 2.01% on AMEX. Generally, no exchange can be blamed for initiating non-positive NBBOs more intensively than others.

The situation is different if we consider intensity of locking (crossing) of certain market centers. For instance, we find that 42.49% and 12.04% of Chicago NBBO quotes are, respectively, locked and crossed. Although not as dramatic, an analogous situation is observed on AMEX, where 12.76% and 3.18% of the venue's NBBO-forming quotes are, respectively, locked and crossed. The rest of the market centers do not show any vivid patterns of being on the passive side of non-positive NBBOs, which supports our earlier suggestion that larger exchanges lock or cross spreads when unable to coerce the less active venues into trading. The data show that AMEX and Chicago are quite active in terminating the locks: 8.58% of AMEX's and 9.13% of Chicago's quotes terminate zero spread periods. The results for crossed markets are much less pronounced, although the two aforementioned exchanges are, once again, the most active in ending non-positive spreads.[13]

4.2. NYSE

While NASDAQ is only the third according to intensity of locking and crossing of its own inter-market; the NYSE seems to cause the majority of non-positive spreads. Specifically, the exchange initiates 59.20% of locked and 66.01% of crossed spread cases. The Pacific Stock Exchange and NASDAQ also actively participate in origination of non-positive spreads with 24.58% and 23.48% of, respectively, locked and crossed markets caused by the former, and 11.30% and 8.23%, by the latter. The NYSE and Pacific are locked most often: both have statistically indistinguishable shares of about 29.5%. NASDAQ's share is 24.14%, which makes it the third most affected venue. Pacific gets its quotes crossed the most, with 34.26% of instances; followed by the NYSE, 23.18%, and NASDAQ, 17.94%. Zero spreads are most often ended by Pacific, 37.47% of all lock terminations; while NYSE and NASDAQ have statistically identical termination shares of about 26.5%. Crossed markets are usually ended by the NYSE, 43.31% of cases, followed by Pacific (30.48%) and NASDAQ (17.76%).

[13] One reason the results for termination of crosses are not as striking as those for the lock cases is because we omit instances where crosses are ended by locks.

In terms of intensity of activity by exchange, we see that the situation with initiations appears to be similar to that on the NASDAQ inter-market – neither venue can be confidently identified as the most active initiator of non-positive spreads. Nonetheless, a clearer pattern can be seen for the locked venues: the exchanges being locked the most are Boston (20.47%), National (18.10%), Philadelphia (11.19%), and Chicago (11.01%). We hypothesize that, similar to the NASDAQ inter-market, these venues are reluctant to change their quotes and are often ignored by the more active markets during the periods of significant price changes. Similar to NASDAQ, the majority of locked markets are ended by the venues whose quotes were locked. For instance, Boston ends 12.33% of zero spreads, followed by National, Chicago, and Philadelphia that carry out, respectively, 6.90%, 6.33%, and 5.78% of lock terminations. Note that the share of lock terminations generally appears to be almost twice as low as the share of being locked (i.e., Boston is locked in 20.47% of cases, but only ends 12.33% of instances). The reason for this finding is twofold. First, at times, zero spread periods are 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 typically done by only one exchange. In particular, a locked (crossed) market ends when all locked (crossed) market centers have updated their quotes, therefore only the last venue to withdraw the stale quote is recorded as the terminator.

Dealer/specialist market centers often stress that they are, by and large, the ones to end locked and crossed markets initiated by the ECN traders who seek access fee rebates and/or faster executions. For instance, NASDAQ dealers complain that they have to manually cease non-positive spreads to ensure continuous transacting, because the SuperMontage trade execution software blocks automatic trading as soon as the NBBO becomes less than or equal to zero. Table 4 provides some evidence on the issue.[14] At the first glance, it seems that the initiators of locked and crossed markets on NASDAQ are marginally more often the ones to end them: the results indicate that about 52% of non-positive spread cases are resolved by the initiators, leaving the rest to the locked venues. Nonetheless, if we look at the statistics by exchange, we discover a rather visible pattern that confirms the dealer/specialists' accusations mentioned earlier: these market makers end more locked (crossed) markets after being locked (crossed) than after initiating (e.g., NASDAQ ends 20.20% of zero spread instances after being locked as opposed to 7.45% after initiating). The

[14] Due to the fact that ECN activity on the NYSE is significantly smaller than that on NASDAQ, we do not include the NYSE inter-market in Table IV. The results for the NYSE, analogous to those in Table IV, are available from the authors upon request.

picture becomes even clearer when one looks at the terminations performed by the ECNs: the majority of times the networks end non-positive spreads when a network is the initiator. As suggested earlier, the locks initiated by ECNs usually result from postings of marketable limit orders with the desired execution price that matches the outstanding NBBO quote. Non-positive spreads of this type can be resolved in two ways: (i) by execution of the locking order or (ii) by the locked market withdrawing the locked quote. In the first situation, we observe a lock ended by the initiator, in the second – by the locked market. At times, an ECN quote may be locked by another ECN. In this case, usually the venue with a lower depth on the inside unlocks or uncrosses the market. Since this venue may appear to be the locked market as well as the locking market, we find that, on a nontrivial number of occasions, ECNs unlock after locking.

Columns (3) – (6) provide some additional evidence on initiator/locked (crossed) market behavior. For instance, Instinet, Island, and Archipelago unlock the market after initiating the lock, respectively, in 48.48%, 42.20%, and 38.39% of all cases. We theorize that ArcaEx, on average, has the deepest limit order book and is therefore able to maintain locking quotes longer than the other two networks, making locked markets unlock the NBBO.[15] The data also show that when NASDAQ quote is locked, it withdraws such a quote in only 29.30% of cases, which leads us to conclude that locking orders from ECNs are more often executed without a change in the locked quotes.

5. Trading and Market Quality

In the earlier sections, we show that instances of non-positive spreads make up a nontrivial portion of an average trading day, especially on the NASDAQ inter-market. We theorize that, depending on an originating market center, non-positive spread instances can be created by a market participant who (i) does not see the quote that he locks or is not willing to wait for an update of a stale quote and does not find it plausible to execute against it, or (ii) submits a marketable limit order to an ECN seeking price/time priority for faster execution or an access fee rebate. In this section, we look at trading of the venues during the non-positive NBBO episodes. Table 5

[15] The same conclusion on depth can be made from the percentage of non-positive spreads ended by the ECNs after being locked: ArcaEx terminates less zero spreads than the other two ECNs after being locked, a phenomenon caused, most likely, by a larger depth on the inside. Goldstein et al. (2005a) show a similar result after considering a number of cancelled ECN orders.

examines trading activity during locked and crossed markets for both NASDAQ and the NYSE sub-samples.

5.1. NASDAQ

In the NASDAQ inter-market, the majority of trades are executed during positive spreads with the shares of positive NBBO executions totaling more than 75%, on all exchanges except AMEX. All venues seem to have execution shares at least twice as high as the percentage time shares of non-positive inside spreads described in Table 2. This fact leads us to conclude that, although the switch to manual executions caused by the non-positive spreads is expected to slow down the trading process, trading during non-positive spread periods, in fact, intensifies.

We do not find any dramatic patterns in trading activity during the non-positive NBBO periods. The data show, however, that while NASDAQ's market share rises from 35.67% to 40.76% when going from positive to negative NBBO periods; the shares of two ECNs: Island and ArcaEx fall, respectively, from 24.78% and 29.55% to 21.52% and 27.35%. The cause of this phenomenon is as follows. If a trader on an ECN posts a locking limit order, trading of the stock between the network and other market makers does not continue until the order is executed.[16] Unless, the locked venue desires to resolve the situation right away, trading with the ECN may not occur for a while. Meanwhile, market makers on the other exchanges may be executing orders around the initiator of the lock (most order handling rules allow for trading through locked and crossed quotes), which increases their market share during non-positive spreads and decreases the share of the locking ECN.

As mentioned above, we find that trading intensifies during non-positive spread periods (e.g., trading frequency almost doubles during zero spreads). On NASDAQ, the number of trades goes up from 11.40 per minute during positive NBBOs to 21.32 per minute during zero spreads. The results for crossed markets are even more impressive, with NASDAQ executing as many as 87.25 trades during one minute of negative spreads. This finding is consistent with most of our hypotheses. For instance, if the locked quote is stale, the orders that accumulated while waiting to execute against it, but were not able to do so due to the sluggishness of the locked venue, will execute elsewhere soon after the NBBO is locked or crossed. Also, if a non-positive spread is

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[16] Trading is still possible within the ECN, if there is a market or a marketable limit order large enough to complete the locking order. In addition, locks between ECNs and NASDAQ are usually resolved by the latter sending an order to be executed on the locking network, adding to the ECN's share of trades.

originated by a rebate- or price/time priority-seeking trader on an ECN, there is at least one trade to be completed – the trade against the locking order. Thus, after a lock by an ECN, the probability of trading is very likely to be close to one, which is by far higher than during the positive spreads, hence, the higher trading frequency. Finally, as we show in the subsequent section, locks and crosses often accompany significant price shifts that, in turn, are often accompanied by increases in volume and frequency and, therefore, cause the data to show higher trading activity during the non-positive NBBO periods.

Average trade size is lower during the non-positive NBBO periods on all venues except Island. For instance, on NASDAQ, the trade size drops from 533 shares per trade to 465 or 362 per trade during locked or crossed markets, respectively. Similar decreases are observed on all dealer/specialist-operated exchanges and on ArcaEx; while the results for Island and Instinet do not show a consistent pattern. This nearly universal trade size decrease is consistent with the notion that, during the non-positive spread periods, a number of trades are executed on the ECNs; therefore the networks' order sizes are likely to govern the inter-market's average. We observe from Table 5 that, on the ECNs, the decrease in the average trade size is not as notable as on the dealer/specialist operated venues or does not occur at all. Since NASDAQ often has to trade with ECNs to end locks, the trade size becomes small. Another reason for the trade size decrease is the fact that trades also occur within the market centers (e.g., NASDAQ dealers trade with each other). Since the non-positive spreads often accompany significant price changes (as shown in the following section), market participants may not be willing to take risk by trading large amounts until the new price is set, causing the trade size to decrease.

5.2. NYSE

In the NYSE inter-market, most of the exchanges execute more than 93% of their orders during the positive spreads. The Pacific Stock Exchange presents a notable exception to this observation, executing only 81.09% of its trades when NBBO is greater than zero. Pacific's share of executions during the locked markets is more than twice as high as the rest of the venues', garnering 10.86% of all trades completed by the exchange. The exchange also executes 8.05% of its orders during negative NBBOs: four times more than the rest of the market centers.

Market shares of some of the venues exhibit notable changes during the locked and crossed market periods. For instance, the NYSE loses about 15% of its regular share of trading volume when the NBBO falls from positive to zero. On the other hand, Pacific and NASDAQ exhibit a different pattern, with both venues' market shares going up by about 6% during zero spreads and by 11.62% on Pacific as well as by 3.99% on NASDAQ at the time of negative spreads. The rest of market centers also show an increase in market share when going from the positive to zero NBBO spreads. These observations are consistent with the stale quote and the ECN orders hypotheses, similar to those discussed for NASDAQ. As shown earlier, the NYSE is most often the venue to lock the NBBO. When an NYSE trader locks or crosses a stale quote, he is likely to send accumulated orders to the market that has the next best price. If this market happens to be one of the remaining regional exchanges, its volume increases after a lock or a cross. In addition, price/time priority-seeking orders are likely to cause increases in order flow on NASDAQ when locking orders are executed against.

Average trade size results for the NYSE-listed sub-sample do not appear as uniform as those for the NASDAQ inter-market. The trade size on Boston, NYSE, and Chicago is higher for non-positive NBBO spread periods than it is for the positive ones; however, on Pacific, NASDAQ and Philadelphia average trade size goes down when the spreads acquire a negative sign. Although inconsistent with the findings for NASDAQ, the more ambiguous trade size pattern on the NYSE does not contradict our general line of thinking: ECNs are not as active on the NYSE inter-market; therefore trades are not executed against orders of small sizes to resolve locks.

Table 6 investigates another issue that is closely related to trading – market quality. Regrettably, we are unable to differentiate between buy and sell trades by means of conventional algorithms such as Lee and Ready (1991) or Ellis, Michaely, and O'Hara (2000), because both procedures fail when the NBBO becomes non-positive.[17] We therefore turn to less sophisticated measures that do not rely on the trade direction indicators. These measures, although less rigorous, are able to shed some light on what is happening to market quality during the locked and crossed periods. Specifically, we compute trade shares according to the price location with respect to the corresponding NBBO and distances between prices and NBBO midpoints. The results provided in

[17] Both algorithms are based on an assumption that customer buy (sell) trades mostly happen at prices above (below) the midpoint. According to the procedures, if a trade price is above (below) the bid (ask) NBBO quote, but is below (above) the NBBO midpoint, the trade is classified as a customer sell (buy). Zero spreads, however, eliminate the possibility of identifying such type of transactions, because, in the case of a customer sell (buy) order, the price is not only going to be higher (lower) than the ask, but also higher (lower) than the corresponding quote midpoint. Ellis, Michaely, and O'Hara's (2000) algorithm uses past prices to identify the direction of the trade. We argue that since locked and crossed markets are often caused by price changes that are already occurring, the effects implied in the procedure may be overpowered and the algorithm may malfunction. The effects only intensify in the case of negative spreads.

Table 6 show that the gap between trade prices and midpoints is the widest during negative spreads and averages three cents for both NASDAQ- and the NYSE-listed securities. As to the positive and zero spread markets, the price is usually different from the midpoint by only one cent. We also find that when the NBBO spread is positive, 92.25% and 93.51% of all trades happen within or at the inside quotes, respectively, on NASDAQ and the NYSE. These shares decrease quite dramatically when the NBBO becomes zero: 76.95% of NASDAQ and 59.16% of the NYSE trades are executed at midpoint, which for the zero NBBO spreads comprises "within and at the inside quotes" category. The percentage of NASDAQ trades executed at the midpoint is higher than that on the NYSE, because of the ECN-originated locks. The gap between the two market centers narrows when the inside spread becomes negative: NASDAQ and the NYSE execute, respectively, 57.36% and 50.57% of their trades within or at the NBBO quotes.

Overall, the results show that the shares of trades executed at prices outside the NBBO increase when the NBBO spread becomes zero or negative. We surmise that this finding is attributable to price shifts that often accompany periods of locked and crossed markets and cause uncertainty among market makers who, in turn, raise the execution costs to compensate for the potential losses.

6. Hypotheses Testing

To provide more evidence for the stale quote hypothesis, we measure for how long an average quote is outstanding before another quote is entered (or becomes active) and locks or crosses the market. As shown in Table 7, for NASDAQ stocks, the average time a quote is outstanding before another quote actively locks the market ranges from 40.03 seconds for quotes coming from ArcaEx to 17.37 minutes (1,042.16 seconds) for Chicago quotes. Locked quotes on AMEX also appear quite old compared to those of the larger market centers, although the difference is not as drastic as in the case of Chicago: an average locked quote on AMEX is only 9.27 minutes old (556.43 seconds) before it is locked – a possible consequence of the quotes invisibility to the market participants. Note that on the rest of the exchanges locked quotes are outstanding for less than or slightly more than one minute. Examinations of passively locked and crossed instances show that on the major market centers these types of non-positive spreads also affect quotations that have not been outstanding long (again, with the exception of the Chicago and AMEX quotes). Overall, the statistics coincide with the stale and invisible quote arguments for less active exchanges, as the quotes being locked (crossed) on AMEX and Chicago appear quote old and may need an update. The situation on the NYSE appears to be similar to that on NASDAQ. It is fairly easy to separate the participating exchanges into two groups according to the age of their locked (crossed) quotes. Three most active venues: the NYSE, NASDAQ, and Pacific have their quotes actively locked after, respectively, 40.60, 45.12, and 108.01 seconds. The rest of the market centers' quotes are substantially older when they are locked, ranging from 434.21 seconds on National to 933.11 seconds on Philadelphia, leading us to conjecture that these markets are often tardy with quote updates and might, at times, be irresponsive to execution requests.

Most of our hypotheses rely on the assumption that locked and crossed markets are caused by significant price shifts. According to the stale quote hypothesis, if the quote is outstanding for a long time, and a stock price change makes it binding; market participants are likely to lock or cross the outdated quote and trade through it. In addition, price shifts may cause high volume on markets that post the best quotes, which sometimes makes traders on other markets initiate locks to avoid having their orders queued or having prices change while their orders are in transit. To investigate this issue; we adopt a procedure similar to that of Cao, Ghysels and Hatheway (2000) who use the RTWPC (relative time-weighted price contribution) to measure strength of signals corresponding to different spread environments during the NASDAQ pre-opening. Our data set is notably different, 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 as follows:

$$MPC_i = \frac{1}{S}\sum_{s=1}^{S}\sum_{d=1}^{D}\frac{\left|\Delta P_{s,d}\right|}{\sum_{d=1}^{D}\left|\Delta P_{s,d}\right|}\times\left|\frac{\sum_{t=1}^{T}\Delta P_{i,s,d}}{\Delta P_{s,d}}\right|, \text{ where} \qquad (1)$$

i – a state of the market characterized by different NBBO spreads signs;

s – a stock in the sample, with $S = 100$;

d – a day in the sample month, with $D = 18$;

t – one of the time periods i during a trading day d;

MPC_i – mean price contribution of a state i;

$\Delta P_{i,s,t}$ – a price change during a spread state i for symbol s on day t.

Term $\frac{\left|\Delta P_{s,d}\right|}{\sum_{d=1}^{D}\left|\Delta P_{s,d}\right|}$ estimates the weight of a day t's price change as compared to the price change during the entire sample month; whereas term $\left|\frac{\sum_{t=1}^{T}\Delta P_{i,s,d}}{\Delta P_{s,d}}\right|$ computes the significance of positive, zero, or negative spread periods in the total price change on day t. Locked and crossed markets, by definition, may accompany falling as well as rising prices. In particular the data show that in a cross section, for certain time periods, negative spreads lead to price increases, while for others – to price drops. In addition, the signal carried by the different types of NBBO spread often changes sign from day to day. To control for this peculiarity, we remove the sign from the significance term in (1) by taking an absolute value. This correction only leaves us with the magnitude of price change, but the altered measure is still able to provide useful insights. Specifically, MPC in Table 8 reveals that most price changes accumulate during the positive NBBOs. Unfortunately, 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, a legitimate 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 the intensity of price contribution (IPC) as follows:

$$IPC_i = \frac{1}{S}\sum_{s=1}^{S}\sum_{d=1}^{D}\frac{\frac{\left|\Delta P_{s,d}\right|}{\sum_{d=1}^{D}\left|\Delta P_{s,d}\right|}\times\left|\frac{\sum_{t=1}^{T}\Delta P_{i,s,d}}{\Delta P_{s,d}}\right|}{Time_{i,s,d}}, \text{ where} \qquad (2)$$

$Time_{i,s,d}$ – denotes the amount of time each spread environment i lasted on a sample day d for symbol s.

By taking the length of different spread environments into account, we are able to show in Table 8 that crossed markets accompany the most intensive price shifts on both NASDAQ and the NYSE. In particular, the IPC ratio for the negative NBBO spreads is 0.28 and 0.25 on NASDAQ and the NYSE, respectively. The changes are not as intense during locked NBBOs, with the ratios equal to 0.03 and 0.04. Positive spread periods are the least intense, with the ratios of 0.003 and 0.002 on the respective inter-markets.

As we suggest earlier, locked and crossed NBBOs may be caused by several factors. It is therefore necessary to verify whether our hypotheses hold in a multivariate cross-sectional regression setting that considers each factor in isolation. Hence, we use several logistic regression models with the dependent variable equal to 1 if the NBBO is locked (crossed) by an offer quote and zero otherwise.[18] The models incorporate several regressors, each controlling for a certain aspect of the arguments suggested earlier, such as *time outstanding* of locked (crossed) quotes on each of the sample markets, magnitude of *price change* in the [-5;5] minute interval surrounding the lock (cross), *spread width* on the locked (crossed) market (or the average width in case of several victims), *volume* in the [-5; 5] minute interval surrounding the lock (cross) on all of the sample venues, and eight dummy variables for the *time of the day*.[19]

According to the outdated quote argument, if a quote posted by a non-responsive venue becomes stale, more active market centers are likely to lock or cross it, if they find trading against the quote problematic. We thus expect the time outstanding variable to have a positive influence on the probability of a lock (cross) on exchanges that are often tardy with quote updates and executions. Regression results in Table 9 show that such markets are AMEX, Chicago, and NASDAQ for the NASDAQ-listed 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, except for NASDAQ in the NASDAQ inter-market. We suggest that, for less active stocks in the sample, dealers may periodically be non-responsive when other markets attempt to execute against their stale quotes or the locked quotes may appear to be auto-quotes. Due to the large number of quotes coming from NASDAQ, this result is not evident from Table 7.

The price change variable is constructed as a sum of price shifts during the [-5; 5]-minute interval surrounding the locked (crossed) quote. If the price is falling, the variable is negative; and the more intensive the change, the larger the absolute value of the variable. According to the price/time priority argument, an ask-initiated lock is more likely to occur when the price is falling, as more customer sell orders accumulate on the venues with best bid quotes, causing traders from other markets to refrain from sending their orders out. In addition, when prices fall rapidly, traders might not be willing to send their sell orders to other venues, because the price may change during

[18] Regression results for the bid quote-initiated locks are consistent with the hypotheses developed throughout the paper and are available from the authors upon request.

[19] Time-of-the-day dummy variables are used to control for intraday volume effects. As the number of locked and crossed spreads is likely to fluctuate during the trading day due to higher quoting intensity, controlling for time of the day is expected to improve the model.

transit. Thus, we expect the coefficient for the price change variable to be negative (negative price change multiplied by a negative coefficient gives a higher probability of a locked (crossed) market). Regression results for both inter-markets confirm this conjecture.

Although it may seem to be the case according to the argument above, significant price changes do not have to be accompanied by long queues: if the market is liquid, price drops do not necessarily cause accumulation of sell orders. We therefore control for spread width on the locked (crossed) market(s), because a narrow spread may be indicative of a queue. As the number of outstanding limit orders increases, new orders seeking price priority are submitted at prices close to quotes on the other side, lowering the potential locked venue's spread. As Table 9 shows, the spread width variable is negative and significant for both inter-markets with the exception of crosses on the NYSE, indicating that a narrow spread on the future locked venue decreases the probability of a zero (negative) NBBO occurrence less than a wide spread, which is consistent with the price/time priority argument.

Finally, we use volume during the [-5; 5]-minute interval surrounding the lock (cross), since high volume on certain venues may lead to formation of queues, making these venues less attractive for speedy transactions. The results show that for all non-ECN market centers (with the exception of NASDAQ for the NYSE-listed sub-sample) high volume is likely to lead to a locked (crossed) market, whereas high volume on the ECNs is, on the opposite, likely to preclude non-positive NBBOs. This result is consistent with the price/time priority argument, as high volume on other markets is likely to entice ECN traders into locking the NBBO to get faster execution. On the other hand, when the volume on the ECNs is high, these traders may as well execute locally, so the probability of a lock (cross) decreases.

Inaccessibility, stale quote and price/time priority 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 two millicents, crossing a quote and losing at least one cent on such a transaction is an unprofitable strategy. This argument is supported by the results of the Goodman-Kruskal (G-K) test in Table 9. 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 the models of crosses than for those of locks. This is consistent with the fact that the models for locks are missing a regressor that would account for rebate-seeking orders coming from the ECNs and NASDAQ. Note that the difference in γ's between the 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 different ECN order types on locked NBBOs with the TAQ trade-by-trade data. We therefore refer to the Dash-5 aggregate data sets to examine whether the number of marketable limit orders still increases the quantity of non-positive spreads originated by the ECNs, when controlling for stale quote and price/time priority considerations. Three Tobit models are used, as shown in Table 10, to investigate the relationship between the *number of zero spreads* originated by a particular ECN during the months of October-December 2003 (censored dependent variable) and the number of *market*, *marketable limit*, *inside limit*, *at the quote limit*, and *outside limit orders* submitted to this ECN. We also use the average *time outstanding* of locked quotes on each market, the number of *shares executed away* from the ECN, and the average *spread width* on locked markets. The results of this analysis are provided in Table 10 and, generally, support the rebate hypothesis, as the only order type that is shown to consistently positively affect the number of locks is *marketable limit orders*. Note that this order type is also used by traders for price/time priority reasons; however, we believe that by including the *spread width* variable we, at least partially, control for queue formation and, hence, price/time priority considerations. Another noteworthy regressor available from the Dash-5 database is the number of shares executed away from the ECN (this variable is not available for Island). It is positive and significant for both Instinet and ArcaEx, consistent with the general notion that the NBBOs are likely to be locked by the ECNs, if the networks do not carry sufficient liquidity, which makes traders seek executions elsewhere.

7. Conclusion

This study documents a large number of locked and crossed NBBO spreads on the NASDAQ and the NYSE inter-markets. We find that the former is locked or crossed about 10% of the time, with all of the 100 NASDAQ-listed 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 3.5% of the trading time. Zero and negative spread periods appear to not be excessively long and are usually resolved within 4.57 – 25.15 seconds from origination, depending on the non-positive spread type and the inter-market of occurrence. We discover that trading intensifies during the periods of non-positive spreads, while the market quality somewhat deteriorates. We, however, refrain from attributing the decrease in market quality to the existence of non-positive spreads. Rather we consider it likely that informational imbalances that are often accompanied by the crossed and locked NBBOs negatively affect market quality.

We discuss several possible causes of locked and crossed NBBOs. Initially, we inquire whether originations of zero and negative spreads can be explained by the lack of coordination among market centers or inaccessibility of their quotations. We only partially accept this argument, based on the fact that most locking and crossing quotes are posted long after locked and crossed ones. We, however, address one caveat – the connectivity problems between AMEX and SuperMontage that often result in the NASDAQ dealers' ignoring "invisible" quotes posted by AMEX. Another cause of non-positive NBBOs confirmed by this study is related to stale quotes that active market makers find unreasonable to trade against. We recognize that certain markets may appear slow with executions against their outstanding quotes or may post binding auto-quotes, delaying trading during the periods of rapid price changes and/or making executions unreasonable. The side of the NBBO quoted by these markets is likely then to be locked or crossed, as active traders post their own quotes that better reflect current market prices. Yet another cause of non-positive spreads has to do with the price/time priority considerations in a multi-market setting. We hypothesize that, sometimes, traders might not be willing to send time-sensitive orders to the market with best quotes, because their information may lose its value while the order is in transit or in queue. These traders are likely to lock or even cross the NBBO to obtain the benefits of price/time priority. Finally, we argue that a non-trivial number of zero spreads is caused by rebate-seeking traders that submit marketable limit orders to the ECNs and NASDAQ. In addition, Island does not allow submissions of market orders, forcing its subscribers into marketable limit orders submissions if they are willing to trade at current market prices.

The recently adopted Regulation NMS urges market participants to avoid non-positive spread occurrences as much as possible. The Commission suggests that locked and crossed NBBOs are "inconsistent with orderly markets" and "create confusion for investors." The Regulation, therefore, suggests to only allow automatic quotes to lock manual quotes and to, consequently, disallow manual quotes to lock automatic quotes. This proposition seems rather discordant with the main arguments of this study. In particular, "invisible" AMEX quotes are very likely to be automatic and, according to the Regulation, will be banned from being locked. Auto-quotes posted by tardy market centers are also likely to be automatic, by definition, so prohibiting market participants from locking and crossing them may cause severe trading disruptions. As to the NBBOs locked (crossed) due to the price/time priority considerations, it can be argued that making it more difficult for informed traders to execute time-sensitive orders may debilitate price discovery. While we agree that price/time priority-caused locks should be limited as they may be unfair to the queued orders on the locked markets, informed traders should have an opportunity to at least cross the NBBO, if it is economical from their standpoint to obtain price/time priority this way. The issue of ECN liquidity and rebates is a complicated one; however, we suggest that pros of decreasing the number of locked markets need to be weighted against the cons of weakened ECN liquidity, price discovery, execution speed, etc.

We conclude that although non-positive NBBO periods frequently disrupt electronic executions and irritate market makers and the SEC regulators, they should be viewed as natural phenomena in contemporary segmented markets; as they allow the markets to correct for stale quotes, information/liquidity mismatches and liquidity shortages. We suggest that the positive effects that accompany locked and crossed markets should be accounted for by the regulators when devising new trading rules, in particular, the Regulation NMS that, in its current wording calls market centers to establish and enforce rules that require avoiding locking or crossing quotations.

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Table 1

Summary Statistics

This table contains summary statistics on quoting and trading activity among trading centers that make market in the 100 most active NASDAQ- and NYSE-listed stocks. Data for November 2003 were obtained from the Trades and Quotes (TAQ) database. November 28th was excluded from the analysis due to a shorter trading day: major markets closed at 1:00 p.m. The analysis includes only quotes and trades that occurred during the regular trading hours, namely, 9:30 a.m. – 4 p.m., EST. For the NYSE sub-sample, we exclude observations that occurred during the first 15 minutes of trading for each day to eliminate the effects of a call auction. Panel A contains the results for the NASDAQ-listed sub-sample, while Panel B describes the NYSE-listed sub-sample. For several markets, the number of stocks quoted and/or traded is given as a range, in which the lower bound represents the day with the lowest quoting and/or trading activity, and the higher number represents the day with the highest activity. Results of pair-wise t-tests for the difference in means are represented by the superscripts.

Panel A: NASDAQ

	AMEX	National (Island)	ADF (Instinet)	Chicago	Pacific (ArcaEx)	NASDAQ
Quoting activity						
Market share, %	3.89[a,a,a,a,a]	9.62[a,a,a,a]	16.67[a,a,a]	0.06[a,a]	41.61[a]	28.16
Stocks quoted, #	73 - 97	100	100	54 - 62	100	100
Trading activity						
Market share, %	0.02[a,a,a,a,a]	24.64[a,a,a,a]	9.93[a,a,a]	0.24[a,a]	28.77[a]	36.38
Average trade size, shares	1,443.25[a,a,-,a,a]	288.04[-,a,a,a]	282.10[a,a,a]	1,411.20[a,a]	343.24[a]	519.68
Stocks traded, #	42 - 61	100	100	65 - 73	100	100

Panel B: NYSE

	Boston	National	Chicago	NYSE	Pacific	NASDAQ	Philadelphia
Quoting activity							
Market share, %	5.15[a,a,a,a,a,a]	2.48[a,a,a,a,a]	8.66[a,a,a,a]	35.40[a,a,a]	26.75[a,a]	12.23[a]	9.33
Stocks quoted, #	100	87 - 91	100	100	99 - 100	100	100
Trading activity							
Market share, %	6.08[a,a,a,a,a,a]	2.34[a,a,a,a,a]	2.98[a,-,a,a]	66.85[a,a,a]	2.97[a,a]	18.28[a]	0.52
Average trade size, shares	458.87[-,a,a,a,a,a]	475.78[a,a,a,a,a]	913.75[a,a,a,a]	1,347.53[a,a,a]	291.03[a,a]	674.62[a]	2,675.77
Stocks traded, #	97 - 100	93 - 98	100	100	97 - 100	100	64 - 76

Superscripts [a], [b], [c], and [-] denote, respectively, significance at 0.01, 0.05, 0.10, and non-significant relationships

Table 2
Percentage of Instances and Length of Locked and Crossed Markets
The table presents the results on the percentage of positive, zero, and negative spread occurrences as fractions of total number of spreads and percentage of trading time. The table also includes results on duration (in seconds) of normal, locked, and crossed markets. *Average time* shows for how long an inter-market is operating normally, is locked or crossed. *Maximum (minimum) time* summarize the maximum (minimum) amount of time a market for a stock is operating normally, is locked or crossed. For *maximum time*, the results are given as a range, in which the lower bound represents the day with the smallest maximum length of normal, locked, or crossed markets, and the higher bound represents the day with the largest period length. *% of time* gives a percentage share of trading time, during which a market for an average stock is operating normally, is locked or crossed. *p*-Values represent the *F* test results for a null hypothesis that the numbers of daily instances are consistent across the sample period for each spread type. The results for *average time* and *% of time* were tested for statistical significance of mean differences between the NASDAQ- and the NYSE-listed sub-samples with the results denoted by the superscripts

	Positive NBBO spread	Zero NBBO spread	Negative NBBO spread
Panel A: NASDAQ			
% of instances	84.84	12.22	2.94
p-value	(*0.59*)	(*0.99*)	(*0.36*)
% of time	89.57***	8.43***	1.51
Average time	67.13***	4.57***	8.84**
Maximum time range	8,652 - 244	1,179 - 91	21,347 - 15
Minimum time	0	0	0
Panel B: NYSE			
% of instances	95.86	2.95	1.20
p-value	*(0.21)*	*(0.34)*	*(0.67)*
% of time	96.37	2.29	1.28
Average time	566.11	6.51	25.15
Maximum time range	TD† - 1,301	1,473 - 52	10,948 - 35
Minimum time	0	0	0

Superscripts ***, **, *, and - denote, respectively, significance at 0.01, 0.05, 0.10, and non-significant relationships
† TD – trading day

Table 3

Locking (Crossing), Locked (Crossed), and Unlocking (Uncrossing) Statistics

The table investigates locking (crossing), locked (crossed), and unlocking (uncrossing) markets. A market center is considered to be an initiator of an active lock (cross), if a quote posted by this market center at time *t* causes the inter-market to lock (cross). An exchange is considered to be an initiator of an unintentional lock (cross), if both ask and bid quotes that lock (cross) the inter-market are posted at the same time (usually, by two different exchanges). Unintentional locking and crossing is rare and does not exceed 1% of cases. For this reason and due to space constraints, we do not report the results on shares of unintentional locks and crosses, although we do include them when calculating percentage of instances. A venue is considered an initiator of a passive lock when it had posted potentially locking quote(s) during the crossed market; and, when the cross ended, this exchange's quotes became active and locked the inter-market. An exchange is considered locked by an active lock, if at time *t*, its outstanding ask (bid) quote is matched by a(n) bid (ask) quote originated at another exchange at time *t*. In case of active crosses, an initiator posts a(n) bid (ask) quote that is that is higher (lower) than the victim's ask (bid) quote. An exchange is considered locked by a passive lock, if at time *t*, its outstanding ask (bid) quote is matched by a(n) bid (ask) quote posted by another exchange at time *t-n* with *n* > 0. A(n) ask (bid) quote posted at time *t* unlocks or uncrosses the previously locked or crossed market at time *t*, if it is higher (lower) than the outstanding bid (ask) quote at time *t*. An ask and a bid quotes posted at time *t* simultaneously unlock or uncross the previously locked or crossed market, if the ask (bid) quote is higher (lower) than an outstanding ask (bid) quote as well as higher (lower) than the new bid (ask) quote. As with the initiation cases, the simultaneous unlocks and uncrosses appear to be rare and are not reported. The inter-market cannot be crossed, unlocked, or uncrossed passively. Due to space constraints, we do not include instances of unlocking by crossing or uncrossing by locking. The results are tested for statistical significance of the differences in percentage shares among exchanges as denoted by the superscripts.

	Initiation of		Locked by		Termination of	Initiation of	Crossed	Termination of
	active locks	passive locks	active locks	passive locks	locks	crosses		crosses
Panel A: NASDAQ: market shares								
AMEX	2.86^{a,a,a,a,a}	1.02$^{a,a,a,a,-}$	12.28^{a,b,a,a,a}	0.44^{c,b,b,a,c}	13.05^{b,a,a,a,a}	8.18^{a,a,a,a,a}	27.07^{b,a,a,a,a}	30.40^{a,a,a,a,a}
National (Island)	9.43^{a,a,a,a}	0.89^{a,a,a,a}	11.35^{a,a,a,a}	0.37^{a,a,a,a}	10.20^{a,a,a,a}	9.51^{a,a,a,a}	7.93^{a,c,a,a}	4.59^{a,a,a,a}
ADF (Instinet)	31.66^{a,a,a}	1.22$^{a,-,a}$	16.83^{a,b,a}	0.84^{b,a,c}	27.61^{a,b,c}	25.40^{a,a,a}	19.17^{a,a,a}	16.19^{a,a,a}
Chicago	0.02^{a,a}	0.04^{a,a}	0.49^{a,a}	0.07^{a,c}	0.16^{a,a}	0.07^{a,a}	1.22^{a,a}	0.04^{a,a}
Pacific (ArcaEx)	34.97^{a}	1.22^{a}	17.95^{a}	1.01^{a}	22.15^{a}	35.21^{a}	15.19^{a}	21.71^{a}
NASDAQ	14.01	2.01	37.58	0.79	26.65	20.91	29.42	26.30
Panel B: NASDAQ: % shares of NBBO quotes, by exchange								
AMEX	2.01	0.71	12.76	0.46	8.58	0.83	3.18	1.94
National (Island)	1.25	0.12	2.23	0.07	1.27	0.18	0.18	0.06
ADF (Instinet)	1.63	0.06	1.28	0.06	1.33	0.19	0.17	0.08
Chicago	1.37	1.93	42.49	6.64	9.13	0.62	12.04	0.25
Pacific (ArcaEx)	0.68	0.02	0.52	0.03	0.40	0.10	0.05	0.04
NASDAQ	0.39	0.06	1.54	0.03	0.69	0.08	0.14	0.07
Panel C: NYSE: market shares								
Boston	0.39$^{b,a,-,a,a,-}$	0.34$^{c,-,b,b,a,a}$	5.41^{a,a,a,a,a,a}	0.09$^{b,a,-,a,-,-}$	3.65^{a,a,a,a,a,a}	0.68$^{-,a,-,a,a,b}$	9.63^{a,a,a,a,a,b}	3.98^{a,a,a,a,a,a}
National	0.54$^{a,b,a,a,-}$	0.22$^{c,-,a,a,-}$	5.22^{a,a,a,a,a}	0.03$^{a,-,a,-,-}$	2.23^{a,c,a,a,a}	0.54$^{a,-,a,a,b}$	5.96$^{a,-,a,a,-}$	0.95$^{a,-,a,a,-}$
NYSE	59.20^{a,a,a,a,}	0.38^{b,c,b,c}	29.58$^{a,-,b,a}$	1.00^{a,b,a,a}	26.34$^{a,a,-,a}$	66.01^{a,a,a,a}	23.18^{a,a,a,a}	43.31^{a,a,a,a}
Chicago	0.38$^{a,a,-}$	0.19$^{b,b,-}$	2.85$^{a,a,-}$	0.06$^{a,-,-}$	1.84$^{a,a,-}$	0.48^{a,a,b}	5.38$^{a,b,-}$	1.60$^{a,a,-}$
Pacific	24.58^{a,a}	0.44$^{-,a}$	29.49^{a,b}	0.44^{a,a}	37.47^{a,a}	23.48^{a,a}	34.26^{a,a}	30.48^{a,a}
NASDAQ	11.30^{a}	0.47^{a}	24.14^{a}	0.05^{-}	26.83^{a}	8.23^{a}	17.94^{a}	17.76^{a}
Philadelphia	0.12	0.14	1.57	0.05	0.91	0.05	3.65	0.50
Panel D: NYSE: % shares of NBBO quotes, by exchange								
Boston	1.40	1.20	20.47	0.36	12.33	0.40	5.97	1.15
National	1.74	0.71	18.10	0.08	6.90	0.29	3.39	0.25
NYSE	0.81	0.01	0.44	0.01	0.35	0.15	0.06	0.05
Chicago	1.37	0.69	11.01	0.25	6.33	0.29	3.41	0.47
Pacific	0.71	0.01	0.92	0.01	1.04	0.11	0.17	0.07
NASDAQ	1.20	0.05	2.75	0.01	2.73	0.15	0.34	0.15
Philadelphia	0.79	0.94	11.19	0.37	5.78	0.06	4.25	0.27

Superscripts ^{a}, ^{b}, ^{c}, and $^{-}$ denote, respectively, significance at 0.01, 0.05, 0.10, and non-significant relationships

Superscript ^{n} denotes inexistence of a pair

Table 4

Non-Positive Spread Termination by Participants' Types: NASDAQ sub-sample

The table investigates instances of unlocking (uncrossing) of the inter-market subdivided into locking (crossing) venues and locked (crossed) venues. In the *by a(n)* columns, the results are shown as percentages of all unlock (uncross) cases; in the *when a(n)* columns, the results are the shares of all unlocks (uncrosses) by an exchange in all locks (crosses) by the exchange. The results are tested for statistical significance of the differences in percentage shares among exchanges as denoted by the superscripts.

	Unlocked				Uncrossed			
	by a(n), %		when a(n), %		by a(n), %		when a(n), %	
	Locking venue (1)	Locked venue (2)	Locking venue (3)	Locked venue (4)	Crossing venue (5)	Crossed venue (6)	Crossing venue (7)	Crossed venue (8)
AMEX	$2.84^{-,a,a,a,a}$	$10.06^{a,a,a,a,a}$	58.87	44.02	$7.52^{a,a,a,c,a}$	$23.47^{a,a,a,a,a}$	54.62	44.80
National (Island)	$5.32^{a,a,a,a}$	$4.18^{a,a,a,a}$	42.20	19.87	$3.08^{a,a,a,a}$	$1.40^{a,-a,a}$	19.27	9.13
ADF (Instinet)	$19.30^{a,a,a}$	$7.65^{a,a,a}$	48.18	24.10	$10.69^{a,a,a}$	$5.22^{a,a,a}$	24.86	14.08
Chicago	$0.01^{a,a}$	$0.16^{a,a}$	21.31	15.53	$0.01^{a,a}$	$0.04^{a,a}$	4.24	1.83
Pacific (ArcaEx)	16.93^{a}	5.88^{a}	38.39	17.26	17.92^{a}	4.23^{a}	30.17	14.39
NASDAQ	7.45	20.20	37.91	29.30	12.39	14.04	35.12	24.66
Overall	51.85	48.13			51.61	48.40		

Superscripts ^{a}, ^{b}, ^{c}, and $^{-}$ denote, respectively, significance at 0.01, 0.05, 0.10, and non-significant relationships

Table 5

Trading Activity during Different NBBO Types

The table investigates trading activity when markets operate normally or are locked (crossed). Panels A and B contain the results for, respectively, the NASDAQ and the NYSE sub-samples. Sub-panels *Activity during normal, locked, and crossed markets (by exchange)* contain the shares of trades completed, on each exchange, during normal, locked, or crossed markets as percentage of total trades executed by the exchange. Sub-panels *Market share* contain market shares of the participating exchanges. *Trading frequency* and *Average trading volume* sub-panels contain, respectively, results of trading frequency analysis in trades per minute and average trading volume in shares. The results are tested for statistical significance of the differences in percentage shares among exchanges as denoted by the superscripts.

Panel A: NASDAQ

	AMEX	National (Island)	ADF (Instinet)	Chicago	Pacific (ArcaEx)	NASDAQ
Activity during normal, locked, and crossed markets (by exchange)						
Positive	68.08	78.25	76.29	78.61	79.90	76.27
Zero	26.10	18.20	19.55	18.50	16.24	19.17
Negative	5.82	3.55	4.16	2.89	3.87	4.56
Market share, % of all trades (by NBBO spread type)						
Positive	0.02[a,a,a,a,a]	24.78[a,a,a,a]	9.74[a,a,a]	0.25[a,a]	29.55[a]	35.67
Zero	0.03[a,a,a,a,a]	24.74[a,a,-,a]	10.71[a,a,a]	0.25[a,a]	25.78[a]	38.49
Negative	0.03[a,a,a,a,a]	21.52[a,a,c,a]	10.16[a,a,a]	0.17[a,a]	27.35[a]	40.76
Trading frequency, trades per minute						
Positive	0.01	7.94	3.12	0.10	9.43	11.40
Zero	0.06	13.02	5.99	0.24	13.71	21.32
Negative	0.51	38.48	18.97	8.77	47.89	87.25
Average trade size, shares						
Positive	1,697	285	280	1,554	344	533
Zero	650	292	287	1,113	342	465
Negative	618	285	277	675	316	362

Panel B: NYSE

	Boston	National	NYSE	Chicago	Pacific	NASDAQ	Philadelphia
Activity During Normal, Locked, and Crossed Markets (by exchange)							
Positive	94.12	94.98	95.94	94.43	81.09	93.31	93.29
Zero	4.30	3.77	2.74	3.59	10.86	4.66	5.08
Negative	1.58	1.26	1.32	1.97	8.05	2.03	1.64
Market share							
Positive	6.03[a,a,a,a,a,a]	2.34[a,a,-,a,a]	67.63[a,a,a,a]	2.96[a,a,a]	2.54[a,a]	17.98[a]	0.51
Zero	7.49[a,a,a,-,a,a]	2.52[a,-,a,a,a]	52.50[a,a,a,a]	3.07[a,a,a]	9.24[a,a]	24.43[a]	0.75
Negative	5.68[a,a,c,a,a,a]	1.74[a,a,a,a,a]	52.46[a,a,a,a]	3.48[a,a,a]	14.16[b,a]	21.97[a]	0.50
Trading frequency, trades per minute							
Positive	0.51	0.20	5.69	0.25	0.22	1.52	0.05
Zero	0.77	0.37	6.94	0.48	1.37	2.66	0.23
Negative	2.02	1.05	10.59	1.62	7.14	6.08	1.12
Average trade size, shares							
Positive	456	478	1,329	908	296	681	2,761
Zero	551	530	1,680	1,253	281	583	855
Negative	571	470	2,793	1,126	263	539	809

Superscripts [a], [b], [c], and [-] denote, respectively, significance at 0.01, 0.05, 0.10, and non-significant relationships

Table 6
Market Quality
The table investigates market quality during the different NBBO types. Due to the 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; as well as outside the NBBO quotes. We also measure the average distance between the execution price and the NBBO midpoint for the different NBBO types. Statistical significance of the differences in means between the distances from midpoint is tested via paired t-tests.

	At midpoint	Inside	At ask	At bid	Outside	Distance from midpoint, dollars
Panel A: NASDAQ						
Positive	4.58	19.86	34.75	33.07	7.75	0.01[-,a]
Zero	76.95	-	-	-	23.05	0.01[a]
Negative	0.77	6.79	24.79	25.01	42.64	0.03
Panel B: NYSE						
Positive	8.76	21.61	33.54	29.61	6.49	0.01[-,a]
Zero	59.16	-	-	-	40.84	0.01[a]
Negative	0.78	3.97	21.27	24.56	49.43	0.03

Superscripts [a] and [-] denote, respectively, significance at 0.01 level and non-significant relationships

Table 7

Age of Locked and Crossed Quotes

The table investigates time outstanding of the quotes that become victims of locking and crossing activity. Instances of locked markets are divided into active and passive subcategories. A lock is considered *active*, if posting of a new quote by one of the sample trading venues at time *t* causes the inter-market to lock (NBBO spread becomes zero) at time *t*. A market is considered to be *passively* locked when a venue had posted potentially locking quote(s) during the crossed market, say, at time *t-n*, where $n > 0$; and, after the crossed market ended, say at time *t*, this exchange's quote(s) formed a new NBBO and locked the market. Under *Max* (*Min*, *Mean*) we report the longest (shortest, average) time period (in seconds) during which quotes are outstanding before they are locked and crossed on each of the sample market centers.

	Active Lock				Passive Lock				Cross			
	Max	Min	Mean	Median	Max	Min	Mean	Median	Max	Min	Mean	Median
Panel A: NASDAQ												
AMEX	TD[†]	0	556.43	537.37	7,049	0	211.48	206.84	TD	0	564.39	549.36
National (Island)	4,495	0	42.91	23.13	1,306	0	14.53	13.29	1,306	0	19.70	16.86
ADF (Instinet)	8,777	0	45.37	21.05	2,643	0	16.45	12.99	2,643	0	20.06	13.21
Chicago	TD	0	1,042.16	956.58	18,760	0	1,604.68	1,596.56	TD	0	1,088.76	1,092.27
Pacific (ArcaEx)	8,802	0	40.03	18.55	715	0	16.00	13.36	1,241	0	15.35	9.60
NASDAQ	8,665	0	76.24	38.14	5,433	0	45.76	39.85	5,433	0	44.83	28.88
Panel B: NYSE												
Boston	TD	0	745.60	664.72	2,446	3	290.98	289.33	TD	0	588.13	567.95
National	TD	0	434.21	360.15	1,838	5	215.50	215.50	9,411	0	355.44	344.61
NYSE	2,670	0	40.60	29.18	656	0	34.54	33.95	816	0	34.01	31.92
Chicago	14,374	0	470.47	437.69	1,554	4	215.33	213.86	14,374	0	377.18	366.99
Pacific	12,582	0	108.01	83.32	11,701	0	276.05	289.57	12,582	0	166.94	166.10
NASDAQ	6,783	0	45.12	36.62	338	0	20.65	20.73	5,058	0	30.08	28.05
Philadelphia	TD	0	933.11	901.73	8,202	3	1,070.86	1,062.86	TD	0	964.43	945.54

[†] TD – trading day

Table 8

Price Contribution of NBBOs with Different Signs

For the sub-samples of the NASDAQ- and the NYSE-listed stocks, we calculate the following two measures of price contribution: Mean Price Contribution

$$\text{MPC} = \frac{1}{S}\sum_{s=1}^{S}\sum_{d=1}^{D}\frac{\left|\Delta P_{s,d}\right|}{\sum_{d=1}^{D}\left|\Delta P_{s,d}\right|}\times\left|\frac{\sum_{t=1}^{T}\Delta P_{i,s,d}}{\Delta P_{s,d}}\right|$$

and Intensity of Price Contribution

$$\text{IPC} = \frac{1}{S}\sum_{s=1}^{S}\sum_{d=1}^{D}\frac{\frac{\left|\Delta P_{s,d}\right|}{\sum_{d=1}^{D}\left|\Delta P_{s,d}\right|}\times\left|\frac{\sum_{t=1}^{T}\Delta P_{i,s,d}}{\Delta P_{s,d}}\right|}{Time_{i,s,d}}.$$

MPC measure provides us with information on which of the three possible NBBO types aggregately leads to the highest price change over the sample period. The measure does not account for the fact that locked and crossed markets are not as lengthy as the positive spread periods. On the other hand, the IPC measure considers the intensity of price changes during the different NBBO types by taking into account the length and frequency of non-positive spreads. The results are tested for statistical significance in mean differences between the time periods to find that all results were statistically different at 0.01 level.

	Normal	Zero	Negative
Panel A: NASDAQ			
Mean price contribution	1.0932	0.6670	0.2933
Intensity of price contribution, per minute	0.0032	0.0278	0.2786
Panel B: NYSE			
Mean price contribution	0.8725	0.2693	0.1962
Intensity of price contribution, per minute	0.0024	0.0402	0.2522

Table 9

Determinants of Zero and Negative Spread Initiations

The table contains results of logistic regressions with zero spreads originated by ask quotes as dependent variables. Dependent variable is equal to one if an ask quote locks the inter-market and is equal to zero otherwise. The following regressors are used: victim's time outstanding, magnitude of price change in the 10-minute interval surrounding the lock (cross), spread width on the locked market (or average of spread widths, in case of several locked markets), surrounding 10-minute interval volume. We also use but do not tabulate eight dummy variables (results are available from the authors upon request) for the time of the day to control for intraday volume effects. The global null hypothesis was tested with the Wald test. Goodman-Kruskal γ is used as a quasi-fit measure.

	NASDAQ		NYSE	
	Lock	Cross	Lock	Cross
Intercept	-5.367***	-6.727***	-6.231***	-8.056***
	(0.000)	(0.000)	(0.000)	(0.000)
Time outstanding (×1K)				
AMEX	0.156***	1.084***		
	(0.004)	(0.000)		
Boston			0.119***	0.175*
			(0.000)	(0.071)
National (Island)	-1.211***	-25.903***	0.143***	0.367***
	(0.000)	(0.000)	(0.000)	(0.000)
ADF (Instinet)	-0.381***	-10.837***		
	(0.000)	(0.000)		
NYSE			-36.406***	-28.214***
			(0.000)	(0.000)
Chicago	0.171***	0.241*	0.198***	0.066*
	(0.003)	(0.071)	(0.000)	(0.079)
Pacific (ArcaEx)	-15.708***	-123.069***	0.133	0.307*
	(0.000)	(0.000)	(0.124)	(0.064)
NASDAQ	0.806*	-8.832**	0.325	1.207*
	(0.064)	(0.026)	(0.217)	(0.071)
Philadelphia			0.057**	0.043***
			(0.024)	(0.000)
Price change (×10)	-0.034***	-0.064***	-0.224***	-0431***
	(0.000)	(0.000)	(0.000)	(0.000)
Locked market's spread width	-8.411***	-0.088*	-0.019***	0.025
	(0.000)	(0.087)	(0.000)	(0.304)
Volume (×1M)				
AMEX	7.966***	9.473***		
	(0.002)	(0.000)		
Boston			4.252***	14.347***
			(0.000)	(0.004)
National (Island)	-1.252***	-4.036***	4.465***	3.469
	(0.000)	(0.000)	(0.001)	(0.720)
ADF (Instinet)	-1.588**	-3.833**		
	(0.037)	(0.027)		
NYSE			1.705***	1.497***
			(0.000)	(0.002)
Chicago	2.301**	0.127*	0.925**	4.806**
	(0.026)	(0.061)	(0.042)	(0.037)
Pacific (ArcaEx)	-0.385***	-1.661***	0.368	0.441*
	(0.000)	(0.000)	(0.845)	(0.071)
NASDAQ	0.329***	0.793***	-0.051***	-1.157***
	(0.000)	(0.000)	(0.000)	(0.034)
Philadelphia			1.236*	3.127***
			(0.062)	(0.000)
Wald's Pr > $\chi 2$	0.000	0.000	0.000	0.000
Goodman-Kruskal γ	0.396	0.760	0.581	0.803

Table 10
Determinants of Zero Spreads Initiated on 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 networks are known to be not as active on the NYSE as they are on NASDAQ. Quantities of market, marketable limit, inside limit, at the quote limit, and outside limit orders reported by the ECNs in November 2003 are obtained from Transaction Auditing Group, Inc. and Instinet Group, Inc. Island did not accept market orders during the sample period. Number of zero spread initiations by an ECN (censored dependent variable), average time outstanding of the quotes on the opposite side of the locked NBBO, and average spread widths on the victims are obtained from TAQ. *p-values* for the heteroskedasticity-robust standard errors are provided in parentheses.

	National (Island)	ADF (Instinet)	Pacific (ArcaEx)
Intercept	66.274	718.599***	1,281.677***
	(0.161)	(0.001)	(0.000)
Number of			
Market orders	N/A	0.294*	-0.018
		(0.084)	(0.495)
Limit orders			
Marketable	0.014***	0.0141***	0.023***
	(0.000)	(0.002)	(0.000)
Inside	-0.001***	-0.012***	0.056*
	(0.001)	(0.000)	(0.057)
At the quote	-0.001	0.003	-0.003**
	(0.147)	(0.139)	(0.038)
Outside	0.000	-0.000	0.000
	(0.179)	(0.230)	(0.743)
Shares executed away	N/A	0.005**	0.012***
		(0.046)	(0.000)
Time outstanding of victim quotes			
AMEX	0.007**	0.560***	0.029***
	(0.028)	(0.008)	(0.005)
Island		-5.159**	-3.559***
		(0.022)	(0.000)
Instinet	-0.071		-9.833***
	(0.823)		(0.000)
Chicago	0.007**	0.090**	0.030
	(0.032)	(0.048)	(0.589)
ArcaEx	0.135	-12.624***	
	(0.861)	(0.000)	
NASDAQ	-0.037	3.196*	5.219***
	(0.867)	(0.079)	(0.000)
Spread width (on victims)			
AMEX	-0.030*	-0.343**	-0.098***
	(0.084)	(0.013)	(0.003)
Island		-813.987	-3,977.581***
		(0.277)	(0.000)
Instinet	-216.641**		110.386
	(0.049)		(0.761)
Chicago	0.017	-0.325**	-0.290*
	(0.571)	(0.012)	(0.074)
ArcaEx	816.230	-13,376.356*	
	(0.167)	(0.074)	
NASDAQ	408.7189	14.231.972	-11,051.705***
	(0.694)	(0.190)	(0.001)
$R^2_{ANOVA} = \sigma^2_{\hat{y}} / \sigma^2_y$	0.971	1.049	1.063
$R^2_{DECOMPOSITION} = \sigma^2_{\hat{y}} / (\sigma^2_{\hat{y}} + \sigma^2_{\varepsilon})$	0.919	0.468	0.796