Price Discovery in the Equity Options Market: An Integrated Analysis of Trades and Quotes*

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ABSTRACT

This article proposes a *price discovery function* that measures the information content of quotes in forecasting the next transaction. We apply this measure to the rapidly evolving U.S. equity options market and perform an integrated analysis on the most recent quotes and transactions from the five options exchanges. We find that the newly founded, fully electronic exchange, the *International Securities Exchange* (ISE), has surged to become the leader in providing more informative quotes. We also find a lack of correlation between ISE's price leadership and its market share in trading activities. ISE leads the herd in providing more informative quotes even on options contracts where they have a market share of less than ten percent. Further analyses of the general properties of quotes and trades indicate that quotes from ISE also exhibit significantly narrower spreads, represent the national best bid-offer a majority of the time, and possess the largest Hasbrouck information share on average. Furthermore, the transactions at ISE happen exactly at the bid or offer 84.48 percent of the time, within the bid-offer 13.71 percent of the time, and outside the bid-ask range only 1.81 percent of the time. These figures illustrate the overall firmness of the ISE quotes and the promptness of the ISE transaction reports.

While ISE leads unequivocally in all our measures, the differences among the four traditional options exchanges —- the American Stock Exchange (AMEX), the Chicago Board of Options Exchange (CBOE), the Pacific Stock Exchange (PCX), and the Philadelphia Stock Exchange (PHLX)— are much smaller, with their relative rankings different under different measures. For example, the modified outcry systems at CBOE and PCX lead over the specialist systems at AMEX and PHLX in providing more informative quotes in terms of both our price discovery function and the information share measure, but the ranking of the average bid-ask spread is more in line with the ranking of the market share in terms of trading volume. The spreads at AMEX and CBOE are narrower than those at PHLX and PCX.

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As multiple listing of securities is becoming the norm of the modern microstructure, the relative information content of quotes from different exchanges for the same or related security has attracted significant interest from academia and industry alike. From the academic perspective, it is interesting to understand which microstructural system generates the most informative signals to the market. In particular, it is important to understand, from the policy making perspective, which microstructure system enhances market competition and encourages the market makers in that system to diligently update their quotes and provide the signals that represent their best possible valuation of the market. From the industry perspective, the multiple sources of quotes can be regarded as noisy trading signals, and it is important to identify which source provides the most informative signal and which source is merely adding noise to the market and therefore can be disregarded in forecasting future price movement and in designing trading mechanisms.

Earlier studies have focused on lead-lag regressions among different exchanges in an attempt to identity the leader of the market in discovering new information about the underlying security. Due to concerns on co-integration, direct regressions on lead-lags have been all but abandoned and replaced by newly developed price discovery measures such as the information share measure proposed by Hasbrouck (1995) and the common factor analysis proposed by Gonzalo and Granger (1995). Nevertheless, both measures focus on quote data only and ignore the potential interactions between trades and quotes.

Ignoring the dynamic interactions between quotes and trades can be problematic. The primary purpose of providing quotes is to attract transactions. If, for some reason, the quotes from an exchange never attract any trade, these quotes are hardly meaningful. Basing the analysis purely on quotes assumes that more informative quotes should lead to more transactions, and that the interactions between the two quantities would be captured by an information measure on quotes alone. Such an assumed link, however, does not always exist in practice. The breakdown happens, for example, when one exchange mimics another exchange's quote plus a fixed spread. With today's technology, the mimicking can be done almost synchronously, with lags of less than a second. Thus, based on a second-by-second quote book, both the information share measure of Hasbrouck (1995) and the common factor analysis of Gonzalo and Granger (1995) would indicate that the two exchanges are comparable in price leadership and informativeness. Yet, obviously, the quotes from the mimicking exchange will almost never be traded on and hence provide no extra information to the market. More importantly, the mimicking exchange can avoid the duty (and potential risk) of market making. Nevertheless, the mimicking exchange can still attract transactions based on other venues such as paying for order flow and/or promising to exercise incoming orders at the national best bid offer (NBBO). Relying solely on existing quote-based price discovery measures and forgoing a careful analysis of the dynamic interactions between quotes and transactions would fail to identify such free-riding behaviors from the mimicking exchange.

In this article, we propose a new measure of price discovery that explicitly considers the dynamic link between quotes and trades. Under this measure, an exchange is not "discovering" if its quotes do not lead to trades. Specifically, we define a *price discovery function* that measures the speed under which quotes from an exchange discover the next transaction. The measure thus focuses on the trade discovery capability of the quotes. In the above example, since the mimicking exchange's quotes never lead to trades, the price discovery function of the mimicking exchange will be uniformly dominated by that of the leading exchange. Therefore, a simple comparison of the price discovery functions between the two exchanges will reveal which exchange is actively performing the role of market making and which exchange is simply taking the free ride.

We apply this new price discovery measure to the rapidly evolving U.S. equity options market and perform an integrated analysis on the most recent quotes and transactions from the existing five options exchanges: The American Stock Exchange (AMEX), the Chicago Board of Options Exchange (CBOE), the International Securities Exchange (ISE), the Pacific Stock Exchange (PCX), and the Philadelphia Stock Exchange (PHLX). We focus on the 50 most actively traded and cross-listed option contracts in January 2002. We find that the newly founded, fully electronic exchange, the International Securities Exchange (ISE), has surged to become the leader in providing quotes more informative of the forthcoming trades. We also find a lack of correlation between ISE's price leadership and its market share in trading activities. ISE leads the herd in providing more informative quotes even on option contracts where they have a market share of less than ten percent.

Further analyses of the option quotes indicate that quotes from ISE exhibit the narrowest spreads, represent the national best bid-offer for a majority of time, and possess the largest Hasbrouck information share on average. Matching the transactions with the quote book, we find that, in general, transactions are reported promptly relative quotes, with no systematic delays. We also find that transactions at ISE happen exactly at the bid or offer for 84.48 percent of the time, within the bid-offer 13.71

percent of the time, and outside the bid-ask range only 1.81 percent of the time. These figures illustrate the overall firmness of the ISE quotes and the promptness of the ISE transaction reports.

While ISE leads unequivocally in both price discovery and the promptness of trade report, the differences among the four traditional options exchanges are much smaller, with their relative rankings different under different measures. For example, we find that the modified outcry systems at CBOE and PCX lead over the specialist systems at AMEX and PHLX in providing more informative quotes in terms of both our price discovery function and the information share measure, but the ranking of average bid-ask spread is more in line with the ranking of the market share in terms of trading volume. The spreads at AMEX and CBOE are narrower than those at PHLX and PCX.

Compared to the vast empirical market microstructure literature focusing on the stock markets, relatively little has been done on the market microstructure of options exchanges. The few known studies on the options market include, for example, Battalio, Hatch, and Jennings (2000), De Fontnouvelle, Fishe, and Harris (2000), Mayhew (2002), Neal (1987), Neal (1992), and Wang (2000). None of these studies directly address the issue of price discovery among different options exchanges. A key reason for this lack of research is that, unlike the stock market, synchronous, high quality trade and quote data on option contracts from multiple exchanges were simply not available until very recently. During the past two years, a series of developments in the options market have significantly improved the quality and availability of the options quotes. In July 2000, the Securities and Exchange Commission (SEC) approved a plan to electronically link the various market centers, as an effort to reduce "trade-through"s and other market segmentations.[1] During the same period, the SEC has also been adopting more stringent quoting and disclosure rules on the options market. For example, while the "firm quote" rule had been implemented in the stock market a long while ago, the rule was finally adopted to the options markets in the United States only on April 1, 2001.[2] Although different forms of "firm quote" had been offered by the various options exchanges before this ruling, the ruling provides a common metric among the different exchanges for how quotes should be posted, how they should be legally binding

[1] See Securities Exchange Act Release No. 43086 (July 28, 2000), 65 FR 48023 (August 4, 2000) ("Linkage Plan").

[2] SEC Release No. 34-43591. Release date: November 17, 2000; effective date: February 1, 2001; compliance date: April 1, 2001.

for trades, and where exceptions apply. This ruling change will significantly alter the quoting behavior of the exchanges due to the legally binding feature of the quotes.

Another important development in the options market is the launch of the first fully electronic options exchange, the *International Securities Exchange* (ISE). ISE started its first day of trading of options on May 26th, 2000. Since its launch, the trading activity at ISE has been increasing at an astonishing speed. On August 8, 2000, just ten weeks after its launch, ISE traded its one-millionth contract and was trading on 70 issues. By November 2001, within just 18 months of its launch, ISE had grown to become the third-largest U.S. options exchange, trailing only CBOE and AMEX among the nation's five options exchanges.[3]

Our paper constitutes the first known study of the price discovery of the options market since the options quotes are required to be firm and also since the launch of the first fully electronic option exchange, ISE. We perform our analysis on one month of data in January 2002, nine months after the firm quote rule was implemented in the options market and 19 months after the inception of ISE. We obtain the data from the most authentic sources: the real time feeds from the Options Price Reporting Authority (OPRA). In 1981, the Securities and Exchange Commission approved the OPRA plan as a national market system plan, pursuant to Sections 11A(a)(2) and 11A(a)(3)(B) of the Act. All of the transactions executed on, and price quotations for options generated by, each options exchange are communicated to the public by OPRA. In particular, our study indicates that, only 19 months after its inception, ISE has surged to become the leader in the options market in providing the most informative quotes, and with the narrowest bid-ask spreads, on major option contracts it is trading on. Given the stark structural difference between this newcomer and the traditional options exchanges, the rapid surge of ISE in both its trading volume and its quote quality has important implications for future structural reforms in the market-making of the options market.

Our analysis of the dynamic interactions between trades and quotes is related to Barclay and Warner (1993), whose objective is to determine what types of trades move and forecast prices. Our price discovery function measures the relation in the opposite direction: We analyze which sources of quotes lead to trades. Also related is the work by Battalio, Hatch, and Jennings (2000), who most recently

[3] The market share is reported in a news release from ISE, based on total volume transacted in all listed options, equity as well as index products, traded during the month of October, 2001.

extend their sample to cover the period of our study and investigate whether the options markets approach that of a national market system. They find that, compared to the options market in June 2000, the market resembles much more closely a national market during our sample period in January 2002. Our analysis complements theirs in finding that ISE is the leader of this new market in providing more informative quotes with narrower bid-ask spreads, in executing trades mostly at or within the bid and ask, and in reporting trades promptly.

The next section of this paper describes the microstructure of the options exchanges, with a focus on the newcomer, ISE, and on the recent development of the options market, particularly the implementation of the firm quote rule. Section II describes the data source, the structure of OPRA, and the criteria for our sample selection. Section III presents our new measure of price discovery. Section IV discusses the results of the price discovery in the options market. Section V provides further analysis of the trade and quote data based on traditional measures. Section VI concludes.

I. Market Microstructure of the Option Exchanges

As of today, five options exchanges provide market-making for equity options under three different structures. AMEX and PHLX apply a specialist structure resembling that used in stock markets. CBOE trades options under a "Designated Primary Market Maker" (DPM), a modification of the original open outcry structure used in the futures pit. PCX follows a similar modified outcry structure, and trades options under a "Lead Market Maker" (LMM). The responsibilities of the DPM or LMM are similar to those of a specialist and include disseminating quotes, providing liquidity to thin markets by trading on his own account, and representing public limit orders. The difference is that options traded under a DPM may also be traded by other market makers. The DPM, however, maintains the right to a certain percentage of the public order flow. Refer to Mayhew (2002) for a more detailed discussion on the evolution of the four traditional options exchanges.

In what follows, we first discuss the microstructure of the newcomer, ISE, and then address the new application of the firm quote rule to the options market.

A. The Microstructure of ISE

The International Securities Exchange (ISE) combines auction market principles with electronic trading. Note that ISE is an SEC registered exchange, not an electronic communications network (ECN) or alternative trading system (ATS). ISE has three classifications of members, all of whom are registered broker/dealers. They include ten Primary Market Makers (PMM), one hundred Competitive Market Makers (CMM), and an unlimited number of broker/dealers functioning as Electronic Access Members (EAM). In the ISE system, floor brokers are not needed since orders are input by broker/dealers directly to the point-of-sale (electronic order book).

Similar to specialists, DPMs, or LMMs, PMMs are market makers with significant market making responsibilities, including overseeing the opening, providing continuous quotations in all of their assigned stock options, and ensuring that customer orders are not automatically executed at prices inferior to those available at other options exchanges. Options traded at ISE are divided into ten groups ("bins"), with one PMM assigned to each bin. In addition to maintaining quotations in their assigned stock options, PMMs may conduct a limited amount of trading (up to ten percent of their quarterly contract volume) in other options traded on ISE. A PMM must purchase or lease a PMM membership. PMMs are not permitted to represent agency orders.

CMMs are market makers who quote independently and add depth and liquidity to the market. Each is required to provide continuous quotations in no less than 60 percent of the stock options in their assigned group. There are up to ten CMMs appointed to each bin of options. In addition to providing quotations in their assigned stock options, CMMs may also conduct a limited amount of trading (up to 25 percent of their quarterly contract volume) in other options traded on ISE. Like a PMM, a CMM must purchase or lease a CMM membership. Also, CMMs are not permitted to represent agency orders.

EAMs are broker/dealers that represent agency and/or proprietary orders on the exchange. An EAM does not purchase a membership. Rather, once approved as an ISE member, an EAM pays an access fee that permits the firm to place orders in all of the options traded on the exchange. EAMs cannot enter quotations or otherwise engage in market making on the exchange. An organization may obtain more than one membership. It is possible to be a PMM in one group of options, obtain several CMM memberships to provide markets in other groups, and have an EAM membership to enter agency and proprietary orders in all groups. Firms that are both market makers and EAMs must conduct those activities separately. A member may not be both a PMM and CMM in the same group of options.

B. The Quality of Option Quotes

A key difference between the equity market and the equity options market used to be that quotes in the options market were not firm. In the past, the SEC and most market participants believed that the imposition of a firm quote requirement on the options market and market participants was not workable. In particular, due to the derivative nature of options, one needs to adjust quotes in numerous series in response to a single price change in the underlying security. In the early 1980s, quotes were updated manually; thus, it would be virtually impossible for a market maker to update its quotes in a timely fashion each time the underlying stock price moved. Hence, the general consensus was that it would be impractical to require options market makers to honor their disseminated quotes.

Nevertheless, due to the development of autoquote[4] and automatic execution systems,[5] firm quotes are gradually becoming practically possible. Thus, before the adoption of the firm quote rule on the options market, each options exchange began to require its market makers to have firm quotes at least for some types of orders. For example, AMEX Rule 958A requires a specialist to sell/buy at least ten contracts[6] at the offer/bid displayed when the order reaches the trading post. CBOE Rule 8.51 generally requires a trading crowd to sell/buy at least the RAES[7] contract limit applicable to a particular options class at the offer/bid displayed when a customer order reaches the trading station. ISE Rule 804 requires a market maker to enter the number of contracts it is willing to buy or sell at its quote and prohibits a market maker from entering a bid or offer for fewer than ten contracts. PCX Rule 6.86 generally requires a trading crowd to provide a depth of 20 contracts for all non-broker-dealer orders at the bid/offer disseminated at the time an order is announced at the trading post. PHLX Rule 1015 requires that public customer orders be filled at the best market for a minimum of ten contracts.

[4] Autoquote systems enable options market professionals to update their quotes in numerous option series simultaneously.

[5] Automatic execution systems provide, in effect, firm quotes for public customer orders.

[6] Each contract is on 100 shares of the underlying security.

[7] CBOE's Retail Automatic Execution System.

Based on these developments, SEC released its ruling on firm quotes on November 17, 2000 (SEC Release No. 34-43591). The ruling adopts amendments to the Quote Rule to accommodate the unique structure of the options market. The amendments permit options exchanges to decide whether or not to collect from their members and make available to vendors the size associated with each quotation in listed options. Instead, exchanges may choose to establish by rule and periodically publish the size for its firm best bid or offer in each options series listed on the exchange. If the rules of the exchange do not require its members to communicate quotation sizes for listed options, responsible broker-dealers that are members of that exchange will be relieved of their obligations under the Quote Rule to communicate to that exchange their quotation size. Instead, each responsible broker-dealer may satisfy its firm quote obligation by executing any order to buy or sell a listed option that is a subject security, in an amount up to the size established by the exchange's rules. An exchange may establish in its rules different firm quote sizes for broker-dealer orders than for customer orders.

If, on the other hand, an options exchange chooses to establish procedures for collecting the sizes of its members' quotes and making them available to vendors, the exchange may permit its members' quotes to be firm at different sizes for customer orders than for broker-dealer orders. In addition, an exchange will have the flexibility to collect and disseminate quote sizes for customer orders and establish by rule quote sizes for broker-dealer orders.

SEC is also adopting an amendment to the Quote Rule to require a responsible broker-dealer to respond to an order to buy or sell a listed option in an amount greater than its firm quote size within 30 seconds by either: (1) executing the entire order; or (2) executing at least that portion of the order equal to the applicable firm quote size, and revising its bid or offer. The Quote Rule requires responsible brokers and dealers to immediately execute an order to buy or sell listed options in an amount equal to or less than its firm quote size. The above ruling became effective on February 1, 2001 and the compliance date was April 1, 2001.

The adoption of the firm quote rule marks an important development in the options market. Before this, due to the lack of a common firm quote rule, the meaning of a certain quote was difficult to interpret. In particular, although each options exchange had some firm quote rules of its own, these rules differed across exchanges and often came with many exceptions, such as fast market conditions. Without a general cross-market ruling, such exceptions are sometimes applied liberally by market makers to avoid providing firm quotes. Given the newly set restrictions on firm quotes, it is interesting to investigate how the different market structures among the five options exchanges compete with one another.

Note, however, that while it is interesting to investigate how the quoting behavior responds to the firm quote rule, an analysis of price discovery remains useful even if the quotes are not legally bound to be firm and hence are purely "indicative." After all, quotes are merely noisy signals posted by the market maker to attract and, sometimes, direct trades. Even if these quotes are not legally binding, they still need to respond to the market demands and make adjustments, under the previous "trade or fade" rule. For example, if the current "indicative" bid/ask for a security is at $5.00 plus or minus five cents, and a big buy market order or a succession of small buy orders comes into the market, the market maker either sells at $5.05, or he has to drop his old quote and adopt a new quote and sell at, say, $6.05. Then the quote price change from $5.05 to $6.05 reflects this market maker's adjustment on his valuation of this security upon the incoming buy orders. Therefore, while it is important to understand the legal meaning of the quotes from a certain market, a price discovery analysis of that market does not completely rely on the firmness of the quotes from that market.

II. Data Source and Sample Selection

Our data are based on electronic message feeds from S&P ComStock XpressFeed. The message contains updates on both quotes and transactions, including both the quote or trade prices and sizes. The data provider is the Options Price Reporting Authority (OPRA). In 1981, the Securities and Exchange Commission approved the OPRA plan as a national market system plan, pursuant to Sections 11A(a)(2) and 11A(a)(3)(B) of the Act. The OPRA plan governs the process by which options market data are collected from participating exchanges, consolidated, and disseminated. The OPRA policy committee, composed of representatives from each participating exchange, implements and, subject to the SEC's approval, amends the policies and procedures set forth in the OPRA plan.

The OPRA committee selected the Securities Industry Automation Corporation (SIAC) as the facility for gathering the last sale and quote information from each of the participating exchanges and consolidating and disseminating such data to approved vendors. All of the transactions executed on, and price quotations for options generated by, each options exchange are communicated to the public by OPRA through the facilities of its processor, SIAC.

Each trade that is executed on an options exchange, as well as each price change quoted on an options exchange, is reported to OPRA as a ”message.” The options markets generate messages for a substantial number of products. Currently, there are approximately 3,900 equity securities and indexes underlying listed option products, and more than 178,000 individual option series. Trade and quote data are generated continuously during the hours that markets are open for each options product listed on each options exchange.

Quote message traffic represents the vast majority of the options message traffic. For example, in February 2000, the average number of quotes per day was 37.5 million, while the average number of trades per day was 183,000.[8] Generally, quotes are generated automatically for individual options series based on changes in the underlying stock price or index value. In other words, every time a price changes for a particular equity security, the quotes for all of the options on that security or an index in which that security is represented may be automatically updated on each exchange that trade those options. This enormous amount of quote message traffic burdens the OPRA system so much that there were periods when the amount of options market data sent by the exchanges to OPRA exceeded OPRA capacity to publicly disseminate it on a real-time basis. On November 27, 2000, the SEC came up with a formula that allocates the message capacity of the OPRA system among the participant exchanges during peak usage periods (SEC Release No. 34-43621).

We select option contracts traded on all five exchanges and across the whole 20 business days in January 2002. We find that during that month there are 70,946 option contracts traded on the five options exchanges, but only five percent (3,397 contracts) of them are traded simultaneously in all five exchanges at least for one day. Of the 3,397 contracts, 835 of them are traded on all 20 business days in January. The other contracts either are not as active or expired during the middle of January.

Trading activities vary significantly among these 835 options contracts. The most actively traded option in terms of both trades and volume was CYQBD, a February 2002 (maturity) call option on CSCO with a strike price at $20.00. The option had 3608 trades (239,100 contracts) over the 20 days

[8]SEC Release No. 34-43621; release date: November 27, 2000.

in January 2002, an average of 180 trades per day. The least active in terms of number of trades was VMFAT, a January 2003 call option on Microsoft with a strike price at $100.00. This option only traded 78 times (7,688 contracts) during January 2002, averaging less than four trades a day. The least active in terms of trading volume was EMCDV with only 120 trades and 709 contracts. It is an April 2002 call option on EMC with strike price at $12.50.

While all the 835 options contracts were traded on all five exchanges, many of them were concentrated on one exchange. In particular, for 290 of these contracts, one exchange took up more than half of the market share in terms of number of trades, and for 567 of these contracts, the market share of one of the five exchanges was more than 40 percent. For our empirical analysis, we focused on the contracts where no exchange dominated with a market share higher than 50 percent. We then chose the 50 most active contracts (in terms of number of trades) from them. The 50th contract, the least active, is CYQND, a February 2002 put option on CSCO with a strike price of $20.00. This contract had 833 trades in January 2002, averaging about 42 trades per day. The quote updates are sufficiently frequent to span the trading activities. For the selected 50 option contracts in January 2002, the median quote updating frequency was about seven seconds.

Table I reports the summary statistics of the 50 options contracts chosen for the empirical analysis. The number of trades in January 2002 for the 50 options ranged from 833 for CYQND to 3,608 for CYQBD, with an average of 1431.0 trades over 20 days. On average, 20.8 percent of the trades occurred at AMEX, 29.6 percent at CBOE, 16.2 percent at ISE, 25.2 percent at PCX, and 8.2 percent at PHLX. Market shares based on the trading volume are also reported in the bottom panel. The figures are similar to those based on the number of trades.

III. The Price Discovery Function: A New Integrated Measure

Price discovery has many layers of meanings. Different measures usually capture different facets of price discovery. For example, the information share of Hasbrouck (1995) captures the contribution of each source of quote to the common random walk component in terms of percentage variation explained. In contrast, the analysis of Gonzalo and Granger (1995) focuses on the loading of each source of quote onto the common factor. While the above two measures are usually applied to different sources of quotes underlying the same or related security, the analysis of Barclay and Warner (1993) focuses on the price change from transaction to transaction. In this section, we define a new measure of price discovery that integrates the quotes and trades together and hence can be used to study the dynamic interactions between quotes and transactions.

Specifically, this new integrated measure of price discovery compares the speeds at which the quote updates from different sources converge to the next transaction. Based on this definition, an exchange leads the market if its quotes consistently reveal the position of the next transaction earlier than other exchanges. Similar to the analysis in Barclay and Warner (1993), we also measure the price changes from one transaction to another transaction. Different from their analysis, we do not focus on the transaction price change, but on how different exchanges update their quotes in *anticipation* of the price change from the previous transaction to the next transaction.

To formalize this idea, let Q_t denote the time-t quote from a certain exchange. It can either be the ask or bid. Let P_j denote the transaction price at the time of the j-th transaction. For now, we do not specifically consider the location of the transaction. Suppose there are N transactions on a certain day. We assume that the quote updates are sufficiently frequent in between transactions.

Let $T_j = t_{j+1} - t_j, j = 1, 2, \cdots, N-1$ denote the time interval in seconds between the jth and $(j+1)$th trades. T_j is random, capturing the randomness in business activity. Since a transaction only happens at the interval of T_j, we can regard T_j as the unit of a random business (transaction) clock.

Within the interval T_j, the market quote will move from P_j gradually P_{j+1}. Provided that the two adjacent transaction prices are different, we define the following movement measure,

$$\mathcal{F}(\tau) \equiv \frac{Q_t - P_j}{P_{j+1} - P_j}, \quad t \in [t_j, t_{j+1}], j = 1, 2, \cdots, N-1, \quad P_j \neq P_{j+1}, \tag{1}$$

where τ denotes a normalized transaction time unit, defined as

$$\tau \equiv \frac{t - t_j}{t_{j+1} - t_j}, \quad t \in [t_j, t_{j+1}], j = 1, 2, \cdots, N-1. \tag{2}$$

As the calendar time t moves from t_j to t_{j+1}, the normalized transaction time τ moves from zero to one, capturing the relative distance to the next transaction. Accordingly, as the market quote Q_t moves from one transaction P_j to the next P_{j+1}, the function $\mathcal{F}(\tau)$ also moves from zero to one, assuming that $Q_{t_j} = P_j$ and $Q_{t_{j+1}} = P_{j+1}$. Thus, how fast $\mathcal{F}(\tau)$ moves from zero to one as the transaction clock τ moves from zero to one measures the speed at which the quotes identify the next transaction. We christen the function $\mathcal{F}(\tau)$ as the **price discovery function**.

Note that if the price discovery is uniform in transaction time τ, $\mathcal{F}(\tau)$ would be a linear function and behave like the cumulative density function of a uniform distribution with domain of $[0,1]$. Its derivative $\mathcal{F}'(\tau)$ is then a constant at unity and can be regarded as the probability density of the uniform distribution. This would be the case if the information is revealed to the market uniformly in between transactions. In practice, however, $\mathcal{F}(\tau)$ and $\mathcal{F}'(\tau)$ do not need to exhibit the properties of a distribution. For example, $\mathcal{F}(\tau)$ does not need to be monotone, nor does it need to be continuous or differentiable. Furthermore, if an exchange provides quotes that do not lead to a transaction, the function $\mathcal{F}(\tau)$ for that exchange will not converge to one as τ approaches one.

In practice, a certain transaction only happens at one of the five options exchanges and hence the transaction price may not be equal to the quotes from a certain exchange at the transaction time. The further away from unity a price discovery function is as the transaction time approaches one, the further away that exchange is in providing relevant quotes. Comparisons of the price discovery functions across different exchanges thus reveal the relative price leadership of these exchanges in providing quotes that are relevant for the next transaction.

Due to the inherent uncertainty of trades and the economy, a certain exchange may discover one transaction earlier, but another later, than other exchanges. Thus, the shape and value of the price discovery function will also depend upon the exact trade interval, j. We drop the dependence of $\mathcal{F}$ on j (and also on the exchange) for notational clarity. In our empirical analysis, we compute sample averages of price discovery function for each exchange across all trades in our sample. The average is performed at a fixed transaction time τ.

We measure the price discovery function based on both bids and asks. Since transactions can occur either at the bid or ask, noises are introduced to the measure by bid ask bounces. In particular, even if the bid/ask quote does not change, the price discovery function will vary when a buy transaction is followed by a sell transaction, as the transaction price will move from the ask to the bid price. We hence do not expect the price function to converge to the theoretical value of one at each transaction time, and we use the sample averages across different times to reduce the fluctuation introduced by the bid-ask bounce.

This price discovery function measures how diligently and accurately an exchange updates its quotes in *anticipation* of the next transaction. In a market where quotes are required to be firm, the market maker has the incentive to anticipate the next transaction and move the quote accordingly before the arrival of the next order. On the one hand, the market maker wants to post sufficiently attractive quotes to attract order flows; on the other hand, the market makers has to avoid being trapped into an unwanted situation such as trading against a more informed customer. The price discovery function across transaction time τ depicts the process of this ex ante quote adjustment in anticipation of the next transaction.

On the other hand, when market makers in an exchange can pay for order flow and promise to execute orders at the national best bid and offer (NBBO), the market makers at that exchange may lose incentive to post attractive quotes, for fear of falling into the trap of an informed customer. Instead, the exchange may decide to mimic another exchange's quotes, but with a significantly wider bid ask spread. In an integrated market, this mimicking exchange's quotes will never be executed upon because they are dominated by the leading exchange. Thus, this mimicking exchange would effectively avoid the duty (and the inherent risk) of market making, but still attract order flows from other non-competitive means. Our measure can effectively identify the mimicking exchange's free-riding behavior by showing that its price discovery function is uniformly dominated by that from the leading exchange. In contrast, when the mimicking is simultaneous and the wider spread is by a fixed amount, neither the information share measure of Hasbrouck (1995) nor the common factor analysis of Gonzalo and Granger (1995) can identify this free-riding behavior. Instead, these measures would indicate that quotes from the leading exchange and that from the mimicking exchange are equally informative.

In a more extreme scenario when quotes are purely indicative, a market maker would not have much incentive at all to anticipate the next transaction or to update the quotes before the arrival of the next transaction. Indeed, they can leave their quotes unchanged until the arrival of the next order. Upon the arrival of this new order, they can adjust their valuation and post a new bid-ask for this new order. Such a process is analogous to a negotiating process and can be observed in certain over-the-counter markets. In such a market, the market marker does not have the need to *anticipate* the next transaction because he is allowed to *react* upon the arrival of the next order. Measuring the price discovery function can reveal this scenario because the estimates of the price discovery function would be very close to zero for all $\tau < 1$ and would jump to one at $\tau = 1$. In contrast, traditional analysis of price changes from one transaction to another is more of an *ex post* analysis and hence could not distinguish these different types of dynamic interactions between trades and quotes. In short, by measuring and analyzing the evolution of the price discovery function from different exchanges and under different markets, one can discern whether an exchange is diligently updating its quotes in a specific market. From the estimated results, one can then analyze the microstructural reasons underlying the observed behavior.

IV. Price Leadership in the Equity Options Market

In this section, we estimate the price discovery function from the most recent trades and quotes on the five options exchanges. The price discovery function of each exchange is estimated in between each pair of adjacent and non-equal trades. They are then averages across different trades at fixed transaction time τ. Comparing the estimated price discovery function for the five options exchanges shall reveal which exchange is the most diligent and the most accurate in updating its quotes in anticipation of the next transaction.

Figure 1 plots the sample averages of the price discovery function for the five options exchanges based on bids (left panel) and asks (right panel). The average is across both the 50 option contracts and across the 20 business days in January 2002. We observe that ISE (circle-solid lines) leads the other four option exchanges in providing quotes more informative of the upcoming transaction. While this leadership holds across the whole spectrum of the transaction time τ and for both asks and bids, the leads increase as the transaction time τ approaches one (the next transaction). Furthermore, the lead is more pronounced for asks than for bids.

Differences between the other four exchanges are much smaller. As the transaction clock τ approaches one, the price discovery function in terms of the bid quotes exhibits the following ranking, from the best to the worst: ISE, CBOE, PCX, AMEX, PHLX. Interestingly, this ranking separates the three major structures of the five exchanges. On top of the ranking is ISE, which combines the auction market principles with electronic trading. The second group includes CBOE and PCX, both of which trade options under a DPM/LMM system, a modified version of the original open outcry structure used in futures pits. The least "discovering" quotes come from the specialist systems adopted at AMEX and PHLX. The ranking based on asks are similar, except that the difference between the last two groups is much smaller, while the leadership of ISE becomes all the more pronounced.

To determine the statistical significance of these differences, we compute the statistical properties of the *price leadership function* of ISE over the other four exchanges. The leadership function, $\mathcal{L}^i(\tau)$, is defined as the difference between the price discovery function of ISE, $\mathcal{F}^{ISE}(\tau)$, and that of the other four options exchanges,

$$\mathcal{L}^i(\tau) \equiv \mathcal{F}^{ISE}(\tau) - \mathcal{F}^i(\tau), \quad i = AMEX, CBOE, PCX, PHLX.$$

A positive measure for the leadership function implies that ISE leads the other exchange in providing quotes more informative of the next transaction. Figure 2 plots the sample average of the price leadership function of ISE (solid lines) and its two-sided 95 percent confidence bands (dash-dotted lines). We observe that the leadership of ISE's quotes becomes more significant as the transaction time τ moves closer to unity. Specifically, bids from ISE begin to become significantly more informative about the next trade than other exchanges when the transaction time passes about 30 to 80 percent. The leadership of ISE's ask quotes is much more pronounced. Its leadership becomes statistically significant over the other four exchanges at as early as ten percent for the transaction time τ. Finally, comparing ISE's leadership over the other four exchanges further confirms the above ranking on the three market structures. Overall, ISE's leadership is more pronounced over AMEX and PHLX than over CBOE and PCX.

Although all the selected option contracts trade at all five exchanges, the relative activity varies significantly. For example, for CYQBD, the most active multiple-listed option contract, CBOE accounts for 43 percent of the trading activity while PCX accounts for a meager 16 percent. In contrast, for QQQBN, the second most active contract in our sample, CBOE only accounts for 12 percent of the trading activity while PCX accounts for 41 percent.

When trading activities of a certain contract concentrate on one exchange, we would expect that this exchange has more incentive to keep its quotes updated in anticipation of the next trade. To investigate how the concentration of the trading activity of a certain option contract is related to the price leadership of that contract, we compute the average price leadership function of ISE over the other four exchanges on that contract,

$$\overline{\mathcal{L}}(\tau) = \frac{1}{80}\sum_{t=1}^{20}\sum_{i=1}^{4}\mathcal{L}_t^i(\tau), \quad i = AMEX, CBOE, PCX, PHLX.$$

We then compute the correlation between this average price leadership function and the market share of ISE on that contract, both in terms of the number of trades and in terms of the trading volume. Table II (left panel) reports the correlation estimates at fixed transaction times τ. Surprisingly, the correlations are very small, and even become negative when we measure the price leadership using bids. The selected scatter plots in Figure 3 further indicate that there is no obvious relationship between the price leadership of ISE and its market share in trading activities. In particular, note that the average price leadership measure for ISE is generally positive even when ISE's market share in trading activities is less than ten percent of the total market.

From the scatter plots, we also observe that ISE leads the market for a majority of the 50 options contracts. The average leadership measure, $\overline{\mathcal{L}}(\tau)$, at $\tau = 1.0$, are positive in terms of bids for 43 of the 50 contracts and are positive in terms of asks for 46 of the 50 contracts.

At one point the scatter plots generate very negative leadership for the bids (-0.15) and very positive leadership for the asks (0.30). Further inspection of the data indicates that this result is from IBMBC (February call on IBM with strike price at \$115). Such anomalous behavior occurs when the market price moves very little during the day, and yet the bid-ask spread is very wide for all five exchanges. For such contracts, the noise induced by the bid-ask bounce dominates the information content in the actual price movement.

On the right panel of Table II, we also report the correlation between the price leadership of ISE for each contract and the aggregate trading activity of that contract on all five exchanges. Again, the correlation is fairly small: slightly positive for bids and moderately negative for asks. The scatter plots in Figure 4 further indicate that the negative (bids) and positive (asks) estimates are largely induced by the one outlier on IBMBC. Overall, the plots are fairly flat.

Figure 5 plots the time series of the daily average of ISE's price leadership over the other four exchanges in January, 2002. While the estimate of the leadership measure varies significantly over time, the conclusion remains the same: ISE's leadership is positive for all days in terms of asks and for all but one day in terms of bids.

In summary, the price leadership of ISE is not a contract-specific or date-specific phenomenon, but a general observation across most multiple listed option contracts and at most business days in January 2002. ISE leads the options market in providing quotes more informative of the next transaction, irrespective of ISE's market share in that contract, or the aggregate trading activity of the contract, or different market conditions at different dates.

Particularly interesting is the lack of correlation between ISE's price leadership and its market share in trading activities. Two interrelated implications follow. First, the relative diligence and accuracy in quote updates is not driven by the relative concentration of the trading activities, but is mostly related to the microstructural differences among the five options exchanges. This is an important observation for future structural reforms on the options exchanges.

Second, the trading activity in the options market is not purely driven by the information content and attractiveness of quotes from a specific exchange. Exchanges with less informative quotes still attract a large proportion of trades, potentially due to market segmentation and/or pay-for-order flow practices. Nevertheless, the fact that ISE became the third largest U.S. options exchange within 18 months of inception shows that providing informative and attractive quotes may still represent an important way of attracting order flows.

V. Further Analysis of Quotes and Trades

The thorough analysis of the price discovery function in the previous section reveals important information on how the quotes and trades interact with one another, how frequently and accurately each option exchange updates its quotes in anticipation of the next transaction. Further analysis of trades and quotes based on traditional measures complements the previous analysis in better understanding the quoting, trading, and reporting behaviors of the five options exchanges. This section does that. We first measure the information share of quotes according to Hasbrouck (1995). We then analyze the general properties of quotes and trades and investigate how different measures compare with one another. We find that although the leadership of ISE is unequivocal under all measures, the rankings of the four traditional exchanges do vary across different measures.

A. Information Share of Quotes

When one security is traded among different exchanges, Hasbrouck (1995) proposes a measure of quote informativeness based on the econometrics of cointegrated vector autoregressions. Formally, consider a price vector $p_t = [p_{1t}, p_{2t}, \cdots, p_{nt}]^\top$, where p_i refers to the price of the same security (say, quotes from different exchanges). In our case, $n = 5$ as we are considering the same options contracts traded on the five options exchanges. Hasbrouck (1995) assumes that underlying all these price quotes is a random walk component that represents the "true" value of the security. The difference between the quotes and the "true" value is regarded as transient noise. As such, quotes from each exchange are non-stationary, but quotes across exchanges are cointegrated. A vector error correction model (VECM) of order k can be specified as:

$$\Delta p_t = A_1 \Delta p_{t-1} + A_2 \Delta p_{t-2} + \cdots + A_k \Delta p_{t-k} + \gamma(z_{t-1} - \mu_z) + u_t, \tag{3}$$

where the coefficient matrices $A_i, i = 1, 2, \cdots, k$, are square matrices of order n, u_t denotes the innovation vector with covariance Ω, and $(z_{t-1} - \mu_z)$ denotes the error correction term with

$$z_t = [p_{1t} - p_{2t}, p_{1t} - p_{3t}, \cdots, p_{1t} - p_{nt}]^\top,$$

and μ_z being the mean vector z_t. The vector moving average representation of the model is

$$\Delta p_t = B_0 u_t + B_1 u_{t-1} + B_2 u_{t-2} + \cdots, \quad B_0 = I.$$

The B coefficients may be calculated by "forecasting" the system subsequent to a unit perturbation. We are primarily interested in the cumulative impulse response functions:

$$C_k = \sum_{i=0}^{k} B_k.$$

The first columns of the C_k matrix describe the prices subsequent to a shock in the first price, etc. Of particular importance is the response to the permanent component by taking the limit,

$$C = \lim_{k \to \infty} C_k. \quad (4)$$

The rows of C are identical. Let c be any row of C, the variance of the common random walk component of the quotes is

$$\sigma_w^2 = c\Omega c^\top.$$

If Ω is diagonal, the information share of the i-th market is defined as

$$IS_i = \frac{c_i^2 \Omega_{ii}^2}{\sigma_w^2}. \quad (5)$$

When Ω is not diagonal, the information share is not uniquely defined. Instead, the lower and upper bound can be determined by considering the Cholesky factorization of the all the rotations of the disturbances.

In estimating the VECM model in (3), we specify a lag of ten minutes (600 seconds). To reduce the size of the parameter set, we apply polynomial distributed lags (Greene (1993)) over lags 1-10 (seconds), 11-20, and 21-30, and then apply moving averages on lags 31-60, 61-120, 121-300, and 301-600.[9] To compute the impact of the permanent component in (4), we let $k = 10,800$ (three hours).

Figure 6 depicts the cumulative impulse response functions of the bid quotes on the left panel and ask quotes on the right panel. These are cumulative price impacts implied by an initial unit shock to the quote in one exchange. Following the paper's general practice, each point is an average of daily estimates across all chosen options contracts and over the 20 business days.

[9]We also experiment with different lags and different averages. The results are qualitatively similar.

By construction, at $t = 0$, the impact is unity on one exchange and zero on others. The five figures under each panel represent a unit initial shock on each of the five options exchanges. In the long run (three hours), the impact for each initial shock is essentially identical for all exchanges. This convergence is a consequence of cointegration. However, the speed of convergence is much slower for the options market than for stock exchanges. For example, Hasbrouck (2002) reports that convergence on quotes of S&P 500 indices happens within ten minutes. This is because trading activities in the options market are far more sparse than that in the stock market. Hence, information assimilation takes significantly longer time.

Further inspection of the impulse response functions in Figure 6 reveals the distinct behavior of ISE from the other four options exchanges. For a unit initial shock to any other exchanges, ISE always responds the fastest and converges to the stationary state the earliest. This is vividly shown by the behavior of the solid lines starting at zero in rows one, two, four, and five. On the other hand, when the unit shock is on ISE (row three), this unit shock has a larger permanent impact on the market than all other cases. The conclusions from bids and asks are approximately the same: The permanent impact of a unit shock on ISE is about 23 percent, that from the other four exchanges is about 20 percent or less.

Table III reports the summary statistics of the information share estimates on bids and asks from the five option exchanges. Consistent with the results on the price discovery function, ISE also has the largest information share (bolded numbers), irrespective of whether the comparison is based on minimum or maximum, bids or asks. Finally, the ranking of the four traditional exchanges in terms of the information share estimates is the same as the ranking based on the price discovery function estimates. Quotes from the (modified) outcry systems (CBOE and PCX) have larger information share estimates than those from the specialist systems (AMEX and PHLX). This result indicates that ISE not only provides quotes most informative of the next transaction, but also explains the largest proportion of variation in the common random walk component.

B. Quoted Spreads

The magnitude of quoted bid-ask spreads is a simple and direct measure of transaction cost when all transactions happen at the quotes. When trades do not always happen on the quotes, the bid-ask spread reveals the aggressiveness of a specific exchange in providing binding quotes. For example, if an exchange always provides an exceptionally wide bid-ask spread but offers to trade at the national best bid offer (NBBO), this exchange is essentially shunning part of its market-making duty by providing non-binding quotes.

To measure the average bid-ask spreads, we divide each day into half-hour periods and compute the average bid-ask spreads for each exchange under each half-hour period. The average is a time average: We first expand the quote updates from each exchange into a second-by-second book and then take the averages within each half hour. Figure 7 plots the average bid-ask spreads for quotes from the five options exchanges. The average is across both time and the 50 options contracts. Consistent with its price leadership role, ISE also provides the narrowest bid-ask spreads. The spread is about five cents narrower than the next best, which is AMEX and CBOE. The widest quotes are from PHLX and PCX. Note that the mean bid-ask spreads are wider early in the morning when the market just opens. The spread then declines as trades proceed, flattening out by noon. This is consistent with the implication of the informational story in, for example, Easley and O'Hara (1992).

We also construct the national best bid and offer, NBBO, by defining the highest bid as the national best bid and lowest ask as the national best ask. We then compute the percentage of bids and asks from each exchange that are on the NBBO, as well as the percentage of quotes that are on the NBBO *alone*. Figure 8 plots the percentage of quotes from each options exchange that are on NBBO and on NBBO alone at different times of the day. The superiority of ISE quotes in terms of percentages on NBBO is very pronounced. About 70 percent of time, ISE's quotes, both bids and asks, are the NBBO. The next best (AMEX and CBOE) only have 50 percent of their quotes on NBBO, a 20 percent difference. About 15 percent of time, ISE's quotes are the only ones that are at the NBBO. The next best is 10 percent lower. The relative ranking is consistent with that from the mean bid-ask spread. It is also interesting to note that, similar to the price leadership result, ISE's relative aggressiveness seems to be more obvious in providing asks than in providing bids.

Finally, note that although the leading position of ISE is unequivocal under all measures, the ranking of the four traditional exchanges in quote spreads is different from the ranking in quote informativeness (price discovery function and information share). In particular, while the quotes from PCX are more informative than those from AMEX and PHLX, the quote spreads from PCX are the widest. As will be seen later, the informativeness of PCX quotes may come from its imperfect (random) mimicking of the best bid offer, but with a wider spread; and the wider spread is sustained by the practice of exercising trades inside their own bid ask quotes, many times at the national best bid offer.

C. Trade Execution and Report

Different exchanges provide quotes with different informativeness and different quoted spreads. It is interesting to understand how these different quoting behaviors affect the trading activity. We first investigate whether trades are reported promptly relative to the reports of quotes. For this purpose, we compute the percentage of trades that fall outside the bid-ask range. To investigate whether there is a systematic delay in trade reports, we shift all trades up progressively by from one second to three minutes and investigate at which number of seconds the percentage of "outside trades" is the minimum. For example, if, on average, trades are reported five seconds after the trade has occurred, we should observe that the percentage of outside trades is at the minimum when we shift the trades forward by five seconds.

Figure 9 plots the percentage of trades that are outside the bid-ask range as a function of the shifted seconds for the reported trades. The percentage of outside trades is the smallest when we do not move the trade forward, implying that, on average, trades are reported without delay relative to quotes at all five options exchanges. Particularly interesting is the plot for ISE, which is the steepest. We conjecture that this is a result of the more frequent quote updating and the narrower bid-ask spread at ISE. Therefore, although there are anecdotal evidence on delayed reports of trades (especially large trades), we do not detect any systematic delay in the overall reports of options trades during our sample period.

Given the overall promptness of the trade report, we investigate whether trades occur at exactly the posted quotes. If transaction often occur outside the quotes, either the quotes are not firm in these scenarios or the trades are reported with a delay. Therefore, comparing the percentage of outside and inside trades at different exchanges provide further information on the quoting and trading behavior of these exchanges.

Specifically, we compute the percentage of the trades that are exactly on, inside, or outside the bid-ask quotes. The result is reported in panel A of Table IV. We find that ISE has the smallest percentage (1.81%) of outside trades and the highest percentage (84.48%) of trades that are exactly on the bid or ask. This implies that at least at ISE, trades are not only reported promptly, but also executed at the posted quotes. Hence, one can conclude that the firm quote rule is implemented effectively at ISE with few exceptions.

In contrast, PCX has the largest percentages of transactions (70.34%) that happen inside their bid-ask quotes. That is, although PCX reports the widest quoted spreads, transactions at PCX mostly happen inside their posted spreads. To understand exactly at which places these transactions occur, we further compute and report in panel B of Table IV the percentages of the inside trades that are outside, on, and inside the national best bid offer (NBBO). Most striking is the result on PCX, where a whopping 83.96 percent of the inside trades happen exactly at the NBBO. This, together with its widest bid-ask spread, implies that PCX trades mostly at the NBBO while quotes mostly far outside the NBBO. This potentially means that PCX attracts order flow by matching the best bid offer, but avoids providing binding quotes and hence shunning part of their market-making duty.

Interestingly, although quotes from PCX are rarely binding and hence rarely useful, these quotes nevertheless turn out to be more informative than those from AMEX or PHLX, whether the comparison is based on the price discovery function or the information share. This implies that PCX may potentially be mimicking a quote series that is more informative than those from AMEX or PHLX. But exactly which series is PCX mimicking? Is the mimicking behavior synchronous or is there a time lag? Does PCX implement a mechanical mimicking strategy or a randomized strategy? We explore answers to these questions in the next subsection.

D. Which Exchange is PCX Mimicking?

If PCX always mimics the quotes from a certain exchange with a n-second lag and a fixed spread, the difference between time-t quote from PCX and the time-$(t-n)$ quote from this leading exchange should be a constant for all t,

$$Q_t^{PCX} - Q_{t-n}^{L} = \text{constant},$$

with this constant being negative for bids and positive for asks. To identify which exchange PCX is mimicking, we run the following set of regressions on both bids and asks,

$$Q_t^{PCX} = a + bQ_{t-n}^j + e_{t,n}^j, \quad j = NBBO, AMEX, CBOE, ISE, PHLX; \quad n = 0, 1, 2, \tag{6}$$

where $e_{t,n}^j$ denotes the regression residuals.[10] Then, the exchange (j) being mimicked by PCX and the number of seconds in the mimicking lags (n) should be identified from the regression that generates the best fit. Furthermore, the slope estimate should be close to unity under the null hypothesis of a fixed spread.

We run the regression on each of the 50 option contracts on each of the 20 business days. We use the R-square estimates as a measure for the regression fit. Table V reports the sample averages of the regression R-squares on bids (panel A) and asks (panel B). We see that the average R-square of regression is the largest when the regression is run on the national best bid or ask (NBBO) with zero lags (the bolded number). This implies that PCX possibly follows the national best bid offer, and does so almost synchronously.

Given a fixed lag, we find approximately the same ranking in terms of the R^2 for both bids and asks. The ranking is, from the largest average R^2 to the smallest, NBBO, ISE, CBOE $\sim$ AMEX, and PHLX. Since quotes from ISE represent the NBBO about 70% of the time (see Figure 8), following NBBO is equivalent to following ISE most of the time. Therefore, it is not surprising to see that ISE follows NBBO in generating the next best R^2 for the above regressions. Furthermore, given a fixed exchange, the regression with zero-second lag ($n = 0$) generates the largest R^2, indicating that the mimicking behavior, when it happens, can be done without visible lags (up to a second).

Nevertheless, the mimicking behavior, if it exists at all, is far from fixed. The highest average R-square of all regressions is less than 0.93, far from perfection, implying that a fair amount of quote movement cannot be explained by the above mimicking regression. The R-square estimates also exhibit large variations across samples. This implies that significant randomization exists in the mimicking behavior of PCX. This can come either as a deliberate strategy or as a result of imperfection in mimicking.

[10] We have also experimented with regressions on the logarithm of quotes, under the null hypothesis that the added spread is proportional to the price level. The average results are very similar to what we have obtained here and hence not reported.

This finding of "randomized mimicking" on PCX is consistent with the different rankings for PCX in terms of quote informativeness and quote spreads. AMEX provides much narrower quoted spreads than PCX, but PCX's quotes are more informative because of its random mimicking of the most informative quotes. Although the randomness in the mimicking behavior and the wider spreads make the quotes from PCX less informative (in terms of both price discovery function and information share) than those from NBBO and ISE, they are nevertheless more informative than quotes from AMEX and PHLX. Note that while a fixed spread may not affect the information share of PCX, the randomness in the mimicking does reduce its information share estimate compared to the leading quotes. In the case of our price discovery function, both the randomization and the wider spreads reduce the ranking of PCX relative to the leading exchange.

VI. Concluding Remarks

We have presented an integrated analysis of the most recent quotes and trades at the five options exchanges in the United States. The analysis indicates that the newcomer to the options market, the International Securities Exchange, has surged to the leading position in posting more informative quotes and with narrower spreads. Furthermore, trades at ISE happen exactly on its quotes 84.48 percent of the time, the highest of all option exchanges, implying that quotes at ISE are firm and trades there are reported promptly. These results have interesting implications for future development on the options market. For example, we observe that the order flows at ISE have increased dramatically since its inception and that it has become the third largest options exchanges in terms of trading volumes. Nevertheless, we find that the leadership of ISE in providing informative quotes not only applies to options contracts for which they possess a large market share, but also to those where their market share is still small. In the future, barring further structural reforms among the traditional exchanges, it is intriguing to see how rapidly orders flow to this most efficient exchange, and how some existing practices such as pay-for-the-order-flow slow down such a process.

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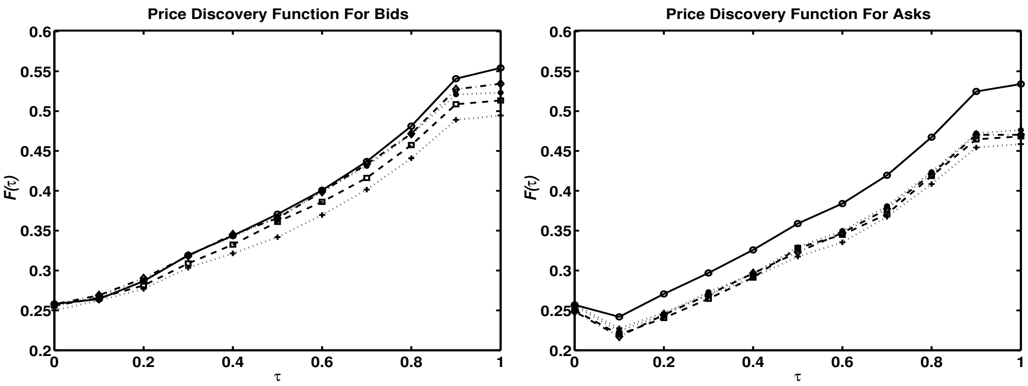

Figure 1. Price Discovery in Equity Options Market

Lines draw the estimated price discovery function $\mathcal{F}(\tau)$ averaged across all 50 option contracts and across all twenty business day in January 2002. The five options exchanges are represented by: square-dashed lines (AMEX), diamond-dash-dotted lines (CBOE), circle-solid lines (ISE), star-dotted lines (PCX) and plus-dotted lines (PHLX). The left panel is computed from bids while the right panel is from asks.

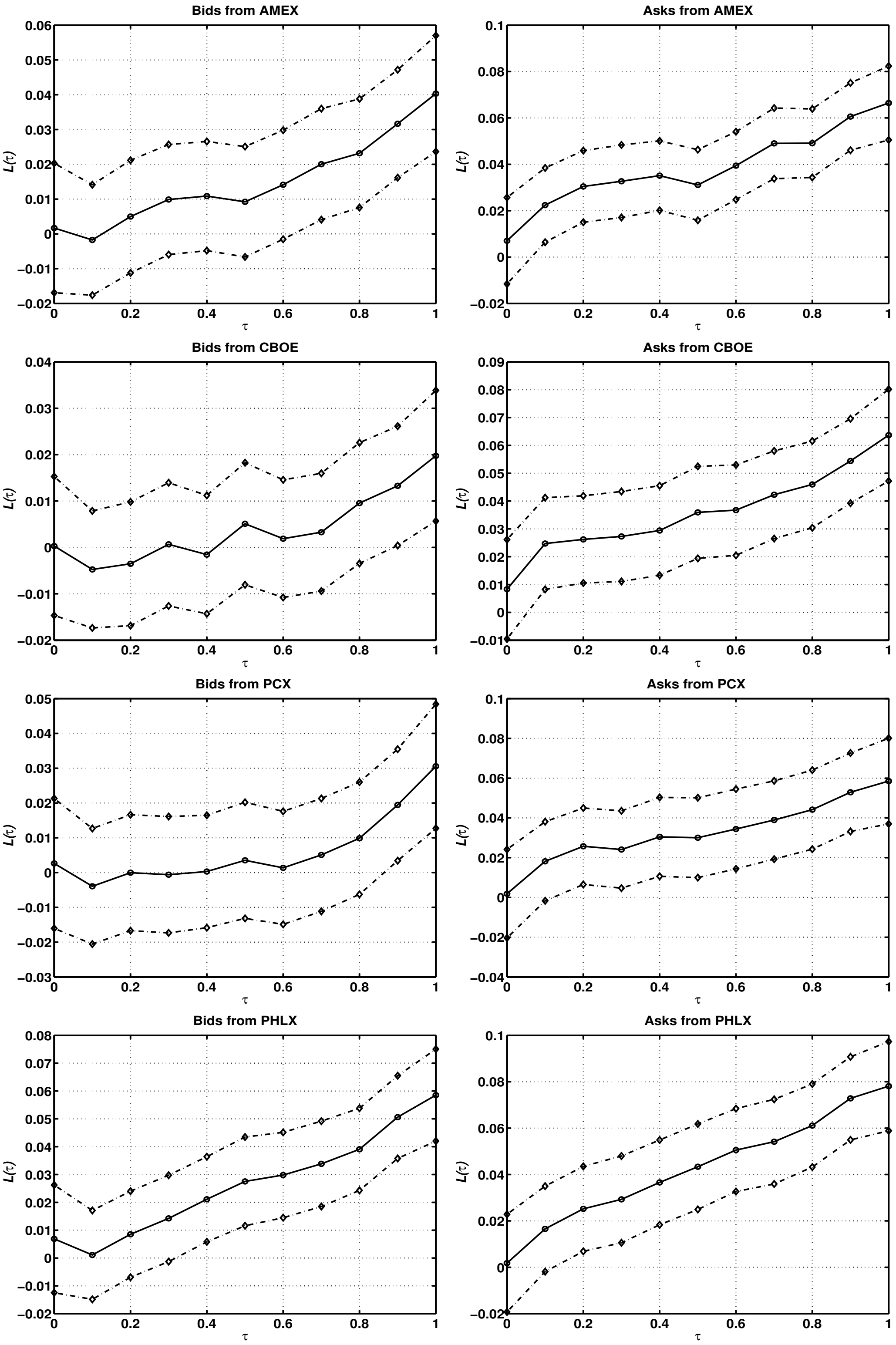

Figure 2. Price Leadership of ISE

Solid lines represent the mean difference between the estimated price discovery function of ISE and that of another exchange, $\mathcal{L}^i(\tau)$. The dash-dotted lines are the two-sided 95 percent confidence interval. The average and confidence intervals are computed based on 1,000 daily observations (50 options over 20 business days).

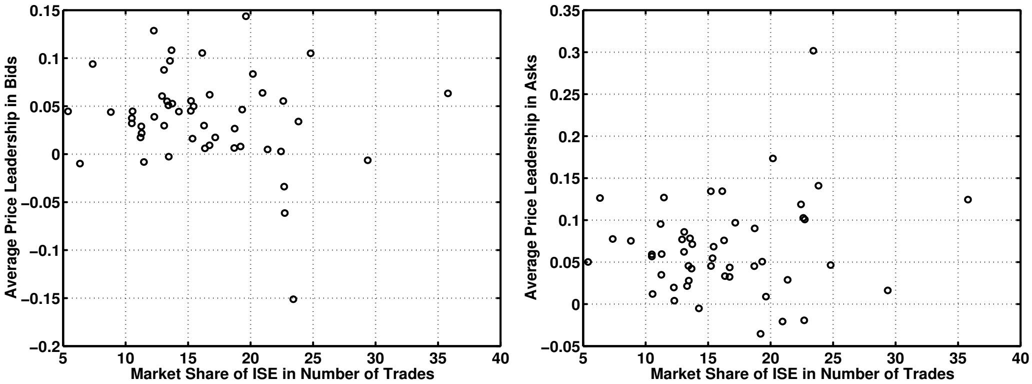

Figure 3. Price Leadership of ISE Versus Market Share

The scatter plots depict the lack of correlation between the price leadership of ISE and its market share in trading activity. The price leadership is the average difference between the price discovery function of ISE and the other four exchanges, measured at $\tau = 1.0$. The market share is defined in terms of number of trades.

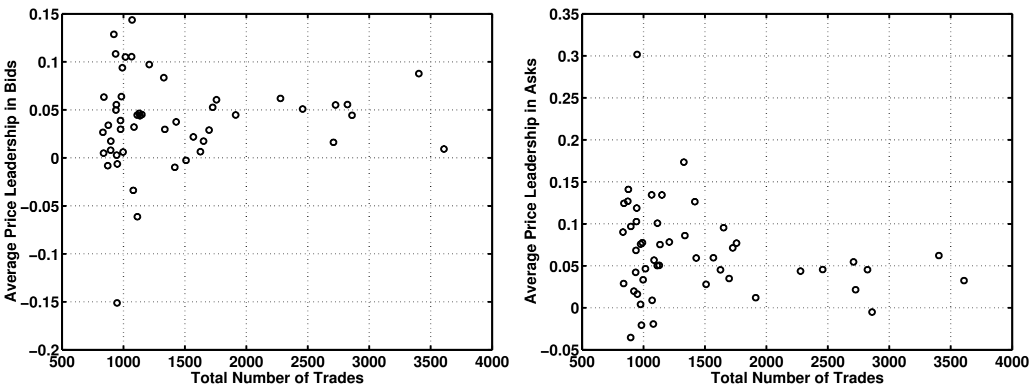

Figure 4. Price Leadership of ISE Versus Aggregate Trading Activity

The scatter plots depict the lack of correlation between the price leadership of ISE and the aggregate trading activity of each options contract. The price leadership is the average difference between the price discovery function of ISE and the other four exchanges, measured at $\tau = 1.0$. The aggregate trading activity is measured in total number of trades over January 2002.

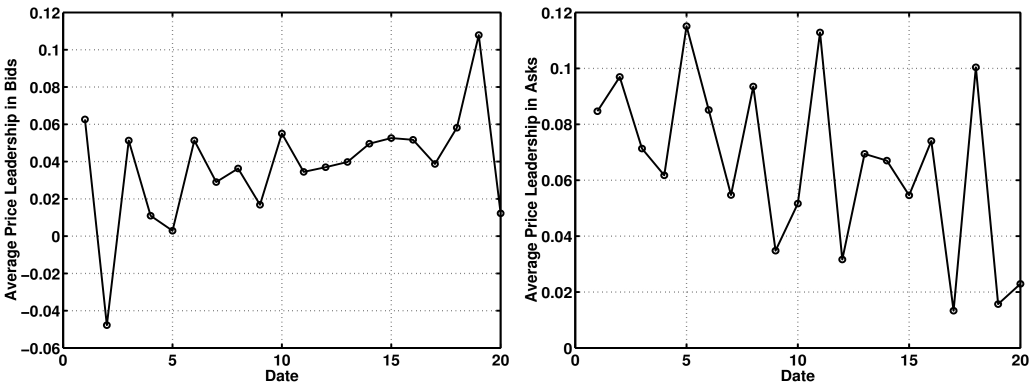

Figure 5. Price Leadership of ISE Over Time

Daily averages of the price leadership of ISE over the other four options exchanges are plotted against the 20 business days in January 2002. The price leadership is the average difference between the price discovery function of ISE and the other four exchanges, measured at $\tau = 1.0$, across all 50 options contracts.

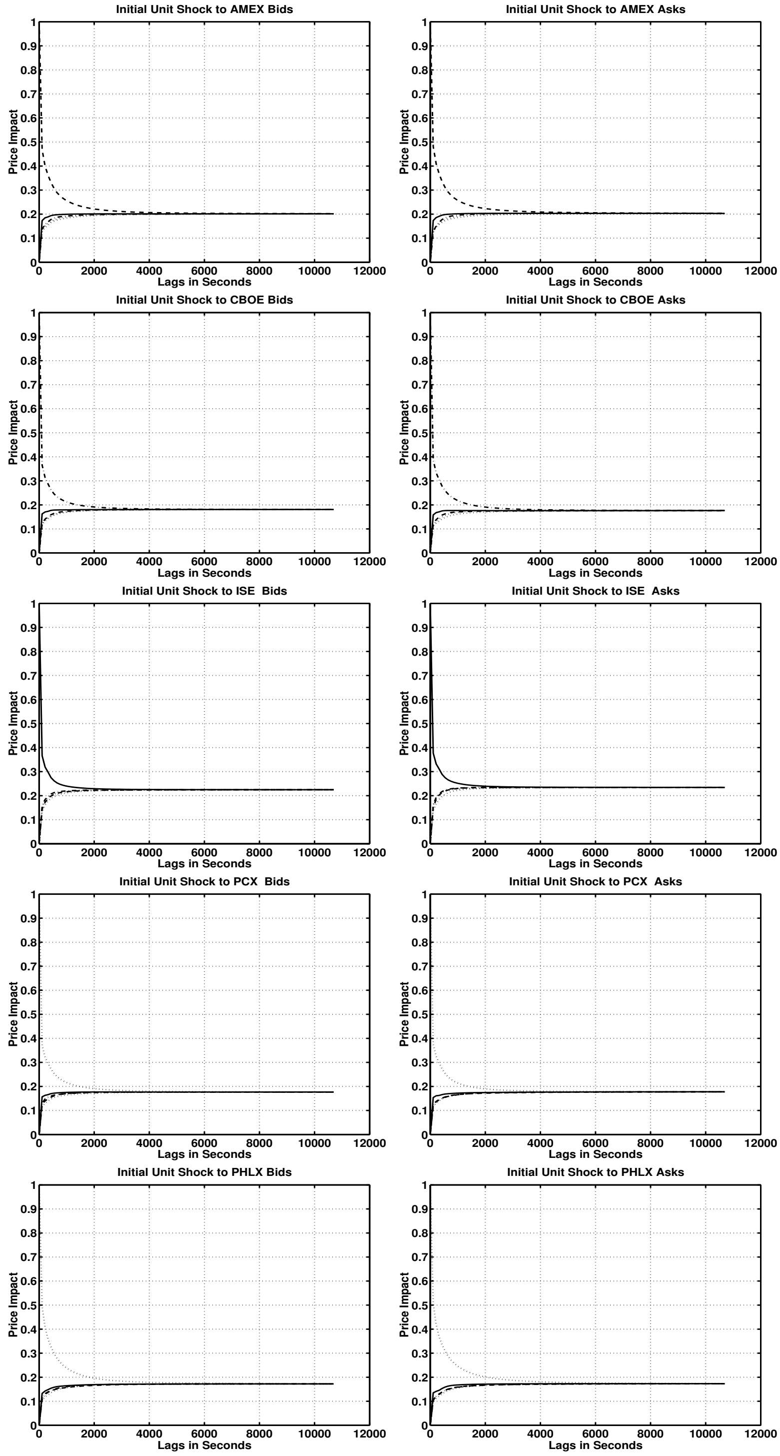

Figure 6. Cumulative Impulse Response Function

The cumulative price impacts subsequent to an initial unit shock to one exchange are implied by the vector error correction model in (3). The models are estimated daily for each option contract with one-second resolution. The plots are grand averages across all option contracts and 20 business days in January 2002. The five options exchanges are represented by: dashed lines (AMEX), dash-dotted lines (CBOE), solid lines (ISE), and dotted lines (PCX, and PHLX). The left panel is estimated based on bids, the right panel on asks.

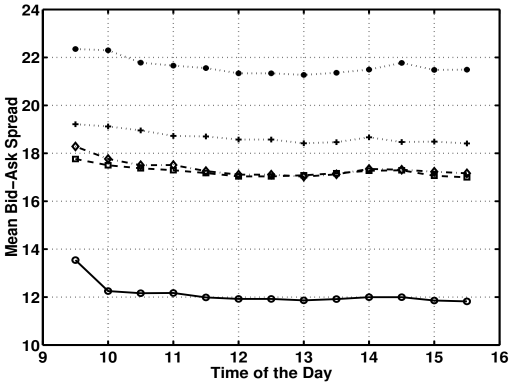

Figure 7. Mean Bid-Ask Spreads for Quotes From the Five Options Exchanges
Lines draw the average bid-ask spreads for quotes from the five options exchanges at half-hour intervals. The five options exchanges are represented by: square-dashed lines (AMEX), diamond-dash-dotted lines (CBOE), circle-solid lines (ISE), star-dotted lines (PCX) and plus-dotted lines (PHLX).

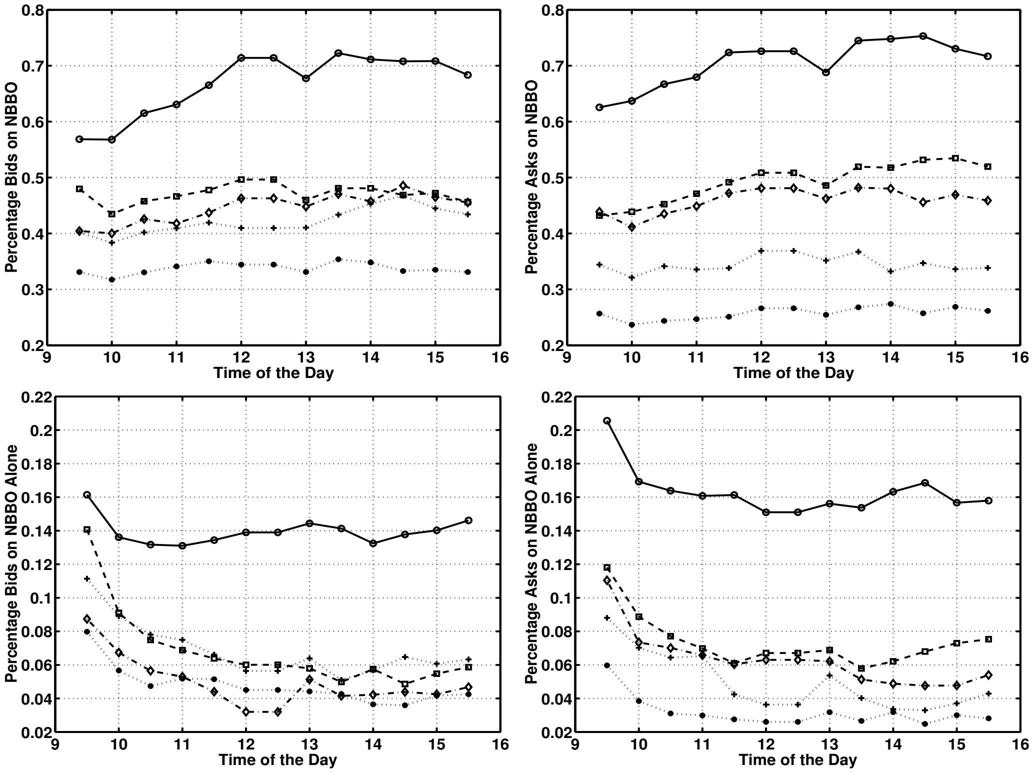

Figure 8. Percentages of Bids and Asks on NBBO (Alone)
Lines draw the percentages of quotes from each options exchanges that are on the national best bid offer (NBBO) and that are on NBBO alone. The five options exchanges are represented by: square-dashed lines (AMEX), diamond-dash-dotted lines (CBOE), circle-solid lines (ISE), star-dotted lines (PCX) and plus-dotted lines (PHLX). The left panel is computed from bids while the right panel is from asks.

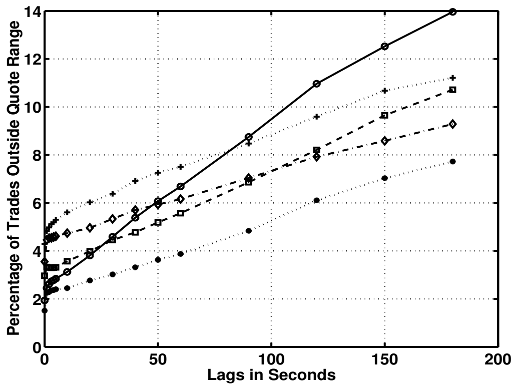

Figure 9. Trade Report Promptness

Lines represent the percentage of trades that are outside the bid-ask quote range as we move the trade forward by zero to 180 seconds. The plots are averages for each options exchange across all 50 options contracts over the 20 business days in January 2002. The five options exchanges are represented by: square-dashed lines (AMEX), diamond-dash-dotted lines (CBOE), circle-solid lines (ISE), star-dotted lines (PCX) and plus-dotted lines (PHLX).

Table I
Trade Composition of 50 Multiple Listed Options

Entries report the sample mean, minimum, maximum, and standard deviation of the total number of trades (top panel) and total trading volume (bottom panel), as well as market shares for each exchange based on trades and volume, respectively. The summary statistics are computed based on the 50 multiple listed options contracts chosen for the empirical analysis in this paper.

Exchanges		A	C	I	P	X
	Trades	Market Share, %				
MEAN	1431.0	20.8	29.6	16.2	25.2	8.2
MIN	833	2.3	9.6	5.4	1.9	2.3
MAX	3608	49.8	49.9	35.8	48.8	30.2
STD	706.3	11.2	13.0	5.8	12.9	6.2
	Volume	Market Share, %				
MEAN	46318.7	27.4	30.1	22.0	11.3	9.1
MIN	7837	4.0	8.8	5.1	0.5	0.7
MAX	239100	50.9	61.0	67.9	33.8	38.9
STD	45813.4	12.7	13.6	11.8	7.2	9.0

Table II
Correlations Between Market Share in Trades and Quote Price Leadership

Entries report the correlation estimates of the price leadership of ISE over other four exchanges with the market share of ISE in the left panel and with the aggregate trading activity in the right panel. The market share and aggregate trading activity are measured in terms of number of trades and trading volume, respectively, as labeled. For each option contract, the price leadership is defined as the average difference between the price discovery function of ISE and the other four options exchanges,

$$\overline{\mathcal{L}}(\tau) = \frac{1}{80}\sum_{t=1}^{20}\sum_{i=1}^{4}\mathcal{F}_t^{ISE}(\tau) - \mathcal{F}_t^{i}(\tau), \quad i = AMEX, CBOE, PCX, PHLX.$$

The correlation is measured across the 50 options contracts of our chosen sample at fixed transaction time unit τ.

	Market Share of ISE in				Aggregate Trading Activity in			
Correlation	Number of Trades		Trading Volume		Number of Trades		Trading Volume	
τ	Bid	Ask	Bid	Ask	Bid	Ask	Bid	Ask
0.0	0.193	0.365	0.118	0.262	0.020	-0.263	0.005	-0.213
0.1	0.090	0.227	0.081	0.239	-0.014	-0.334	0.005	-0.275
0.2	-0.047	0.213	0.050	0.189	-0.051	-0.369	-0.013	-0.307
0.3	-0.110	0.108	-0.077	0.107	0.106	-0.272	0.077	-0.215
0.4	-0.127	0.105	-0.081	0.126	0.096	-0.227	0.065	-0.187
0.5	-0.040	0.140	-0.027	0.174	0.100	-0.256	0.044	-0.230
0.6	-0.095	0.181	-0.023	0.156	0.038	-0.247	0.006	-0.229
0.7	-0.128	0.203	-0.058	0.154	0.044	-0.293	0.020	-0.255
0.8	-0.216	0.148	-0.056	0.129	0.051	-0.240	0.010	-0.215
0.9	-0.211	0.175	-0.012	0.205	0.033	-0.257	-0.022	-0.237
1.0	-0.178	0.148	-0.005	0.195	0.071	-0.228	-0.025	-0.199

Table III
Information Shares of Option Quotes

Information share statistics are based on a vector error correction model of bids (panels A and B) and asks (panel C and D) from the five option exchanges: AMEX, CBOE, ISE, PCX, PHLX. The model is estimated at each day for each of the 50 option contracts for January 2002. The table reports the summary statistics of these daily estimates.

Exchanges	AMEX	CBOE	ISE	PCX	PHLX
		A. Max Information Share From Bids			
MAX	0.836	0.881	0.942	0.845	0.801
MEAN	0.196	0.226	**0.266**	0.215	0.143
MIN	0.000	0.000	0.000	0.000	0.000
STD	0.166	0.169	0.178	0.172	0.143
		B. Min Information Share From Bids			
MAX	0.814	0.880	0.941	0.843	0.780
MEAN	0.178	0.203	**0.247**	0.196	0.132
MIN	0.000	0.000	0.000	0.000	0.000
STD	0.159	0.161	0.174	0.164	0.138
		C. Max Information Share From Asks			
MAX	0.810	0.943	0.973	0.984	0.835
MEAN	0.189	0.210	**0.280**	0.215	0.147
MIN	0.000	0.000	0.000	0.000	0.000
STD	0.162	0.166	0.181	0.169	0.150
		D. Min Information Share From Asks			
MAX	0.810	0.943	0.966	0.981	0.834
MEAN	0.173	0.191	**0.261**	0.197	0.137
MIN	0.000	0.000	0.000	0.000	0.000
STD	0.158	0.158	0.177	0.162	0.146

Table IV
Percentage of Trades Outside (On, Inside) the Bid-Ask Quotes

Entries in panel A report the percentages of trades at each exchange that are outside, on, and inside that exchange's bid-ask quote range. For trades that are inside the quote range, we further report in panel B the percentage of these inside quotes that are outside, on, and inside the national best bid offer (NBBO). The estimates are averaged across all trades on the selected 50 option contracts during January of 2002 at each options exchange. The last row reports the total number of trades at each options exchange during the sample period.

Exchanges	AMEX	CBOE	ISE	PCX	PHLX
		A. Percentages Out Of Total Trades			
Outside BA	2.83	3.47	1.81	1.48	3.55
On BA	59.35	43.00	84.48	28.19	51.93
Inside BA	37.82	53.53	13.71	70.34	44.52
		B. Percentages Out Of Inside Trades			
Outside NBBO	5.67	8.85	7.63	6.96	5.54
On NBBO	75.98	74.99	68.86	83.96	78.33
Inside NBBO	18.35	16.16	23.51	9.09	16.13

Table V
The Mimicking Behavior of PCX

Entries report the R-square estimates of the following regression:

$$Q_t^{PCX} = a + bQ_{t-n}^j + e_{t,n}^j, \quad j = NBBO, AMEX, CBOE, ISE, PHLX; \quad n = 0, 1, 2,$$

where Q_t^j denotes the quote (bid in Panel A and ask in Panel B) from exchange j at time t (seconds). The regression is performed daily on each option contract. Entries report the sample average (standard error in parentheses) of the estimates across the 50 option contracts and over the 20 business days in January, 2002.

(j,n)	0		1		2	
			A. Bids			
NBBO	**0.9275**	(0.2354)	0.9198	(0.2486)	0.9196	(0.2486)
AMEX	0.8288	(0.2718)	0.8287	(0.2718)	0.8286	(0.2718)
CBOE	0.8326	(0.2599)	0.8326	(0.2599)	0.8325	(0.2599)
ISE	0.8750	(0.2433)	0.8750	(0.2432)	0.8749	(0.2432)
PHLX	0.8140	(0.2672)	0.8139	(0.2672)	0.8138	(0.2672)
			B. Asks			
NBBO	**0.8488**	(0.2186)	0.8486	(0.2186)	0.8485	(0.2186)
AMEX	0.8057	(0.2411)	0.8057	(0.2411)	0.8056	(0.2411)
CBOE	0.8009	(0.2544)	0.8008	(0.2544)	0.8008	(0.2544)
ISE	0.8310	(0.2262)	0.8310	(0.2261)	0.8309	(0.2261)
PHLX	0.7885	(0.2918)	0.7884	(0.2917)	0.7883	(0.2917)