The Effect of the Introduction of Cubes on the Nasdaq-100 Index Spot-Futures Pricing Relationship

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This paper examines the impact of the introduction of the Nasdaq-100 Index Tracking Stock (referred to as Cubes) on the pricing relationship between Nasdaq-100 futures and the underlying index. Observations obtained from tick-by-tick Nasdaq-100 futures transactions and index value data support the hypothesis that the introduction of Cubes in March 1999 has led to improvements in the Nasdaq-100 index futures pricing efficiency. Both the size and frequency of violations in futures price boundaries appear to be reduced. Furthermore, there appears to be an increase in the speed of the market response to observed violations. These results are attributed to the increased ease in establishing a spot Nasdaq-100 index position after the introduction of the tracking stock. © 2002 John Wiley & Sons, Inc. Jrl Fut Mark 22: 197–218, 2002

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INTRODUCTION

Stock index futures first appeared in 1982 with the introduction of Value Line Composite index futures contracts. Since that time there has been explosive growth in the number and volume of index futures contracts traded worldwide. Research on the spot-futures pricing relationship has also been quite extensive since the introduction of these contracts. The results show that significant deviations from a no-arbitrage relationship appear to exist. However, whether these deviations represent real arbitrage opportunities or exist due to market frictions remains to be resolved.

Early research by Modest and Sundaresan (1983), Figlewski (1984), MacKinlay and Ramaswamy (1988), as well as later work by Yadav and Pope (1994), suggests that exploitable arbitrage opportunities exist in index futures contracts. Alternatively, research by Chung (1991), Klemkosky and Lee (1991), and Miller, Muthuswamy, and Whaley (1994) suggests that most apparent arbitrage opportunities are a function of underestimated transaction costs, nonsynchronous trading estimations, or market immaturity. More recently, Garrett and Taylor (2000) and Tse (2000) show that mean reversion in futures mispricing is driven by arbitrage activity rather than by microstructure effects.

One problem faced by arbitrageurs is that in order to establish the cash leg of an index arbitrage, these traders must buy or sell baskets of stocks. Actual and implicit costs associated with such transactions can be significant and variable depending on market conditions, which reduces the profit of any potential arbitrage opportunity. Recently, the financial community has attempted to address this issue by creating a market for tracking stocks that allows for the purchase or sale of the entire index with one trade. These stocks have significantly reduced the size and variability of the costs associated with the purchase or sale of the spot position. Examples of such instruments include the Standard and Poor's Depository Receipts (SPDR – pronounced Spiders), which track the S&P 500 Composite index, and Toronto 35 Index Participation units (TIPs), which track the Toronto 35 Index. If previously found mispricings are a function of such spot market costs, one should expect a significant tightening of the spot-futures relationship after the introduction of the tracking stocks.

Park and Switzer (1995) study changes in the pricing efficiency of index futures contracts after the introduction of TIPs. They show that mispricing of Toronto 35 Index futures appears to have decreased after TIPs were introduced in 1990. This finding is interpreted as evidence that TIPs create new interest in index arbitrage by reducing transaction costs in the spot market. Switzer, Varson, and Zghidi (2000) report a reduction in positive mispricing of S&P 500 futures contracts after introduction of Spiders.

The aim of this paper is to further investigate the effect of the creation of tracking stocks on the cash–futures pricing relationship. This is accomplished by estimating the effect of the introduction of the Nasdaq-100 Index Tracking Stock on the pricing relationship between Nasdaq-100 futures contract and the underlying index. The tracking stock began trading on the Amex on March 10, 1999 under the symbol QQQ. These instruments, also referred to as "Cubes," are created by a unit investment trust, which holds a portfolio of stocks included in the Nasdaq-100 index.[1] Cubes attracted significant investor interest soon after their introduction and since that time have been one of the most actively traded stocks in the United States.

This study employs tick-by-tick transactions data for Nasdaq-100 futures and 15-s interval data for the Nasdaq-100 index. The Nasdaq-100 is chosen for several reasons. First of all, Cubes are actively traded and were introduced several years after the introduction of the futures contract. This allows for an accurate point of comparison to estimate the effect of the increased ease in establishing a spot position on the spot-futures pricing relationship. Second, there are minimal dividends on the index, which makes for one less variable to consider in observing the spot-futures pricing relationship. Finally, there have not been any studies to date that test pricing efficiency of the actively traded Nasdaq-100 futures contract.

This study differs from those of Park and Switzer (1995) and Switzer et al. (2000) in several important respects. First, this study uses tick-by-tick transactions data as opposed to daily or hourly observations used in previous research. High-frequency data allow for a much more accurate estimation of the incidence, magnitude, and speed of adjustment to violations of the futures price boundaries. Second, unlike the previous studies, this analysis controls for changes in price volatility and

[1]Cubes were designed to approximate performance of the index at a ratio of 1/20. This ratio was changed to 1/40 after the two-for-one split announced on February 14, 2000. The annual operating expenses of the trust are limited to 0.18%. While relatively low, these expenses exceed the dividend yield of the Nasdaq-100 index portfolio. Thus, no dividend distributions to shareholders are expected. The downtick rule that prohibits short selling on the downtick does not apply to Cubes. Cubes currently trade as stocks on the Amex, NYSE, Nasdaq, and regional exchanges with regular brokerage commissions applicable. Additional information about Cubes can be found at www.nasdaq-100.com.

futures trading volume in the examination of changes in the spot-futures pricing relationship after the introduction of Cubes. Finally, as previously mentioned, this is the first study to observe pricing relationships for the Nasdaq-100 futures contract.

The results show a significant reduction in boundary violations for the Nasdaq-100 index futures contract immediately after the introduction of Cubes. This reduction appears to be consistent across various times to maturity and market conditions and cannot be explained by changes in futures trading volume or index volatility. Furthermore, a larger percentage of apparent violations disappear within a 2-min lag period. These results support the notion that the introduction of tracking stocks on indexes tightens the spot-futures pricing relationship.

The remainder of the paper is structured as follows. The second section describes the theoretical spot-futures pricing relationship and the hypotheses tested in the paper. The third section describes the data, sample selection, and method to be employed. Finally, the fourth and fifth sections discuss the empirical results and provide some conclusions, respectively.

THEORETICAL SPOT-FUTURES PRICING RELATIONSHIP AND ARBITRAGE

Most studies of index arbitrage assume that the spot-futures relationship follows a cost-of-carry model. The theoretical futures price in this model is:

$$F_t^* = S_t e^{(r-d)(T-t)} \tag{1}$$

where S_t is the spot price of the stock index at time t; r is the risk-free interest rate; d is the dividend yield on the stock index portfolio; and T is the expiration date of the futures contract. The rate r is often referred to as carrying charge, since it represents the opportunity cost of carrying the spot asset to maturity of the futures contract. The buyer of stock index securities incurs the opportunity cost of his funds but receives dividends. Therefore, the futures price should equal the cost of buying the spot index securities, including the opportunity cost, adjusted for dividends paid during the remaining life of the futures contract. As the futures contract approaches maturity, the futures price converges to the value of the spot index. Equivalently, the basis, that is, the difference between the futures price and spot index value, converges to zero at expiration. The implicit assumptions underlying the cost-of-carry model include perfect markets, constant carrying charges, and constant dividend flow to the index stocks.

Futures mispricing, x_t, is defined as deviation of the actual futures price F_t from its theoretical value, deflated by the value of the underlying index at time t:

$$x_t = \frac{F_t - F_t^*}{S_t} \qquad (2)$$

The futures price can fluctuate around the theoretical value within the boundaries determined by transaction costs without triggering arbitrage trades. The no-arbitrage condition can be described by the following inequality:

$$|x_t| - c_t \leq 0 \qquad (3)$$

where c_t is the time t present value of the sum of transaction costs that have to be incurred to conduct arbitrage. The transaction costs relevant to index arbitrage include bid-ask spreads, round-trip commission fees in both the cash and futures markets, and market impact costs[2] in both markets. When inequality (3) is not satisfied, a program trader can exploit the violation by selling index futures and buying index securities or taking the reverse positions. When the futures price exceeds the upper price boundary, "buy" programs are triggered that make orders to buy the index securities and simultaneously sell index futures contracts against those positions. When the futures price drops below the lower boundary, "sell" programs execute reverse transactions.

Temporary violations of futures price boundaries can be driven by arrival of new information or noise trading. Possible sustained violations can be explained by short-sale restrictions in the stock market and the lack of arbitrage capital that represent potential hurdles to index arbitrage, as well as by underestimated transaction costs. Arbitrageurs are not always able to profitably exploit the observed boundary violations because of execution lags.[3]

This paper investigates whether the introduction of Cubes has led to significant changes in Nasdaq-100 spot-futures pricing relationship. Possible reasons for improvements include smaller transaction costs,

[2]Market impact costs represent customer price concessions for large trades. When large orders are placed, such concessions become necessary for two reasons. First, market makers in the cash market maintain firm quotes only for limited transaction volumes. Second, traders in futures exchanges are not obligated to take the other side of the customers' orders.

[3]Arbitrage transactions are triggered by computer programs but are typically executed in open-outcry markets. There is a possibility of adverse price changes during the execution lags between the moment when arbitrage opportunity is identified and actual execution of the arbitrage transactions.

shorter execution lags, smaller tracking risk,[4] and fewer short-sale restrictions in the cash index market when Cubes are used in arbitrage. One would therefore expect that for all reasonable levels of transaction costs and execution lags:

H1. *The frequency of ex post violations of futures price boundaries decreases after the introduction of Cubes.*

H2. *The frequency of ex ante violations of futures price boundaries decreases after the introduction of Cubes.*

Prior to the introduction of Cubes, short arbitrages, defined as buying futures contracts and selling the spot index, could be executed only on an uptick. Such tick-sensitive orders are riskier because they take longer to execute.[5] Therefore, if the downtick rule is an impediment to short arbitrage,[6] violations of the lower boundary should be relatively more frequent before introduction of Cubes. One can expect the asymmetry in frequency of positive and negative violations to decrease after introduction of Cubes because Cubes can be shorted on the downtick. This expectation has the following testable implication:

H3. *With symmetric futures price boundaries, the relative frequency of violations of the lower boundaries falls after the introduction of Cubes and such violations are eliminated faster.*

DATA AND METHODOLOGY

The results presented in this paper are based on an analysis of Nasdaq-100 Stock Index values[7] and transactions data for regular Nasdaq-100

[4]It is costly to replicate stock indexes that include several hundred stocks. Arbitrageurs often attempt to approximate such indexes by using representative stock baskets. Although this strategy is easier and cheaper to implement, it increases riskiness of arbitrage because the stock basket will not track the index perfectly. Sofianos (1993) argues that the stock basket approach should be used only when the mispricing is large enough to compensate for the tracking risk.

[5]According to Sofianos (1993), arbitrageurs should use the tick-sensitive orders only when the mispricing is large enough to compensate for the extra risk.

[6]Results reported by Chung (1991) and Chan and Chung (1993) indicate that short-sale restrictions in the cash index market, such as ban on short selling imposed on some institutional investors and the downtick rule, have a potential to significantly impede short arbitrage. However, there is no consensus in the literature on this issue. For example, Neal (1996) demonstrates that the short-sale restrictions appear to have little effect on the mispricing because they can be avoided by direct sales from institutions that have long spot positions.

[7]Stocks in the index do not trade continuously. The last transaction prices used to calculate the index may be "stale" and may not be indicative of the actual state of the market at the moment when the index value is recorded. As a result, the reported value of the index tends to lag its "true" value. Harris (1989) discusses this nonsynchronous trading problem and shows that it can be eliminated in real time. Some studies including Chan (1992) and Chung (1991) calculate the index by aggregating individual stock prices. However, these studies consider smaller indexes, such as Major Market Index (MMI), which consists of only 20 stocks. Attempting to replicate the Nasdaq-100 index by tracking all of its stocks would be too computationally difficult.

futures contracts traded on the CME. The sample period extends over the 336 trading days from July 1, 1998 to October 29, 1999. The sample is divided into two subperiods of about eight months each: the first from July 1, 1998 to March 9, 1999 (172 trading days) before introduction of Cubes and the second from March 10, 1999 to October 29, 1999 (164 trading days) after introduction of Cubes.

Nasdaq-100 index values, obtained from Tick Data, Inc., are provided at 15-s intervals. Each index observation includes date, time, and index value. The data for regular Nasdaq-100 futures contracts, obtained from the Commodity Futures Trading Commission (CFTC), contain the symbol and expiration month of the contract, futures price, date, and time of the transaction to the nearest second. As a proxy for the opportunity cost in the calculation of futures mispricing, the study uses continuously compounded three-month T-bill middle rate obtained from Datastream.[8]

The cash market opens at 9:30 a.m. and closes at 4:00 p.m. (EST). The futures market opens at 9:30 a.m. and closes at 4:15 p.m. (EST). It takes about 30 minutes for all index stocks to start trading. Consequently, index values reported during the first half-hour of cash market trading can be significantly affected by the "stale" prices. To avoid this potential problem, observations occurring during the first 30 minutes of trading are deleted from the sample. The initial data include 219,225 futures trades and 471,757 index values reported between 10:00 a.m. and 4:00 p.m. (EST) from July 1, 1998 to October 29, 1999.

Nasdaq-100 futures contracts expire in March, June, September, and December each year. For every trading day, only the contract with the largest number of trades is considered.[9] Futures trades marked as canceled, corrected, or inserted are removed from the data set. Observations reported out of time sequence are also eliminated, as they are likely to contain errors. To compute the mispricing series, futures prices are synchronized with the spot index values using a MINSPAN procedure suggested by Harris, McInish, Shoesmith, and Wood (1995). If there is no futures trade at the exact time of the reported index value, the closest futures observations within the previous 7 seconds and the next 7 seconds are considered. When only one futures trade meets this

[8]Neal (1996) shows that the implied opportunity cost of index arbitrage exceeds the T-bill rate by 88 basis points. To see if our basic results are sensitive to the choice of opportunity cost, we repeated our tests using the one-month CD middle rate as the opportunity cost. On average, the CD rate was about 15 basis points higher than the T-bill rate during our sample period. The results (not shown) were not significantly different from the reported results received using the T-bill rate. One-month LIBOR (on average, about 59 basis points higher than the T-bill rate during our sample period) consistently overvalues the futures.

[9]Trading activity typically shifts from the futures contract approaching expiration to the next available contract during the second week of the expiring contract's month.

criterion, a spot-futures pair is formed. If both a leading and a lagging futures trades are obtained, the closer trade is used to form the pair and the other one is discarded. Ties are broken in favor of leading futures trades.[10] The data filtering and matching criteria yield a total of 150,697 spot-futures pairs for the sample period.

The empirical method of this study is similar to that used by Chung (1991). In calculation of the mispricing series, the simple version of the cost-of-carry model defined in equation (1) is used. The dividend yield on the Nasdaq-100 index is extremely low. For example, the dividend yield was 0.07% in 1998. Therefore, one can ignore dividends in the calculation of the fair price of the Nasdaq-100 futures. Studies by Neal (1996) and Sofianos (1993) show that the assumption of the basic cost-of-carry model that arbitrage positions are kept open until expiration of the futures is quite unrealistic. They find that most arbitrage positions are liquidated before expiration with the early closing option effectively reducing transaction costs of arbitrage. Therefore, if violations of transaction cost boundaries with the basic model are found, one would expect even greater frequency of violations of the same boundaries with a version that includes the early closing option.

As such, ex post and ex ante violations of the futures price boundaries are calculated for several levels of transaction costs and execution lags. Ex post violations are defined as those in which the violation of a chosen transaction cost boundary is first observed. Ex ante violations are simulated arbitrage trades that are triggered by an ex post violation, executed after a lag, and result in a profit. In an examination of ex ante violations, one must first identify ex post violations and then estimate profitability of the resulting simulated arbitrage trades that are executed after a lag. This paper considers transaction costs of 0.15, 0.20, 0.35, and 0.50% of the index value and execution lags of 30 seconds, 1 minute, and 2 minutes.[11]

[10]Chan (1992) shows that futures price changes tend to lead changes of the cash index and price changes of individual stocks in the index by several minutes. The lead-lag relationship between the two markets cannot be completely explained by nonsynchronous trading because it is observed even for the most actively traded stocks. This relationship seems to imply that the futures market reacts to new information faster than the cash market. Sofianos (1993) shows that when futures and cash legs in index arbitrage are not established simultaneously, the futures leg is established first more often than the cash leg. However, time stamping on futures trades is likely to lag by a few seconds, as trading occurs by open outcry.

[11]Chung (1991) uses transaction costs within the range from 0.5 to 1.0% of the index value and transaction lags of 20 seconds, 2 minutes, and 5 minutes. Sofianos (1993) assumes total transaction costs of actual index arbitrage trades are about 0.4% but shows that effective transaction costs are significantly reduced by early liquidation of positions. Dwyer, Locke, and Yu (1996) show that the mispricing necessary to trigger index arbitrage, i.e., the effective transaction cost, should be about one-half of the round-trip transaction costs. They estimate this threshold at approximately 0.2%. Also, using a 1989–1990 data set of program trades, Harris, Sofianos, and Shapiro (1994) estimate the average lag between submission and execution of orders at about 2 minutes.

As a preliminary test, this study considers the change in average daily futures mispricing after the introduction of Cubes by using an autoregressive model with four lags defined in the following equation:[12]

$$|x_t| = \beta_0 + \beta_1 D_t + \beta_2 CV_t + \beta_3 FT_t + \beta_4 ET_t + \sum_{i=1}^{4} \varphi_i |x_{t-i}| + \varepsilon_t \quad (4)$$

where $|x_t|$ is the daily average of absolute mispricing; D_t is a dummy variable that equals 0 during the pre-Cube period and 1 afterward;

$$CV_t = \frac{100\%}{\overline{S}_t}\sqrt{\frac{\sum_{\tau=1}^{n}(S_\tau - \overline{S}_t)^2}{n-1}} \quad (5)$$

is daily coefficient of variation of the spot index (S_τ is the spot index price, $\overline{S}_t$ is the daily average of the index, and n is the number of observations per trading day); FT_t is daily number of futures trades divided by the number of minutes in each particular trading day; and ET_t is time to expiration of the futures contract divided by the average time to expiration for the sample period.

The dummy variable is included in the regression to test for a structural shift in mispricing after the introduction of Cubes. A negative and significant coefficient of the dummy will indicate a decrease in average absolute mispricing. The variables *CV*, *FT*, and *ET* are used as controls for factors that could significantly affect the mispricing. Four lags of the dependent variable in the regression model are employed to eliminate autocorrelation in the regression residuals.

While a possible reduction of average mispricing is of interest, the main hypothesis is that there is an ex post decline in the frequency of relatively large mispricings after introduction of Cubes. To test this hypothesis, the following autoregressive model is employed:

$$V_t = \beta_0 + \beta_1 D_t + \beta_2 CV_t + \beta_3 FT_t + \beta_4 ET_t + \sum_{i=1}^{4} \varphi_i V_{t-i} + \varepsilon_t \quad (6)$$

where V_t is the daily number of ex post futures price violations of the 0.2% transaction cost boundary divided by the number of hours in each particular trading day. The 0.2% boundary is chosen because a higher boundary would lead to a significant number of zero observations of the

[12]Visual inspection of the correlogram for the mispricing, index volatility, and number of futures transactions series shows that the series are stationary. Augmented Dickey–Fuller and Phillips–Perron tests of the series reject the null hypothesis of a unit root at the 1% significance level. This result supports the conclusion of stationarity.

dependent variable. Again four lags of the dependent variable are used in the regression. The other independent variables are the same as those in equation (4). A negative coefficient of the dummy will support Hypothesis 1.

White's test and the Breusch–Pagan test indicate that OLS residuals of equations (4) and (6) are heteroscedastic. To correct for heteroscedasticity, both equations are estimated using the following multiplicative heteroscedasticity model for the variance of the error term:

$$\sigma_t^2 = \sigma^2(e^{\gamma' Z_t})^2 \tag{7}$$

where Z_t is the matrix of observations of variables CV, FT, and ET that could influence variance of the error and γ' is the parameter vector that represents impact of each of these variables. After the correction for heteroscedasticity, the White's test and the Breusch–Pagan test are no longer significant.

The Jarque–Bera normality test shows that the residuals of both regressions are non-normal. For this reason, the regressions are estimated with quasi-maximum likelihood (QML) method. According to Bollerslev and Wooldridge (1992), QML estimation gives consistent estimates under non-normal distribution of residuals.

The following regression is used to test the hypothesis of a reduction in the frequency of ex ante violations of the futures price boundaries:

$$APR_t = \beta_0 + \beta_1 D_t + \beta_2 CV_t + \beta_3 FT_t + \beta_4 ET_t + \varepsilon_t \tag{8}$$

where APR_t is the number of ex ante futures price violations of the 0.2% transaction cost boundary (calculated with the execution lag of 2 minutes) in each particular trading day divided by the number of ex post violations of the same boundary that occurred during the same day.

The choice of a 0.2% transaction cost boundary leads to a zero value of APR for approximately 20% of the daily observations, since on those days no ex ante violations of the selected transaction cost boundary are observed. Because the dependent variable is truncated at zero, a Tobit model is estimated. The residuals, ε_t, in the Tobit model are assumed to be normally, independently and identically distributed, although residuals for the zero observations of the dependent variable are not observed. To correct the potential problem of heteroscedasticity of Tobit residuals, the model is estimated using a multiplicative heteroscedasticity model for the error term similar to that used in estimation of equations (4) and (6).

EMPIRICAL RESULTS

Ex Post Mispricing Results

Summary statistics for ex post mispricings of the Nasdaq-100 futures contracts over the sample period are reported in Table I. The average absolute value of mispricing declines from 0.14 to 0.10% of the index value after the introduction of Cubes. The two-sample test of medians indicates a significant decline in the average and variability of the absolute value of mispricing in the post-Cube period. Furthermore, while first-order autocorrelation of mispricing changes is significantly negative throughout the sample period, suggesting mean reversion in the mispricing series, the mean reversion occurs faster in the post-Cube period indicating a faster market response to mispricing. The first-order autocorrelation of the mispricing series during the pre-Cube sample period is as high as 0.85, indicating high persistence in mispricing, and

TABLE I

Summary Mispricing Statistics of Nasdaq-100 Futures Contracts for July 1, 1998 to October 29, 1999

	7/1/98–3/9/99	*3/10/99–10/29/99*	*7/1/98–10/29/99*
Number of trading days	172	164	336
Number of observations (index-futures pairs)	61,543	89,154	150,697
Average mispricing[a]	**0.062 (0.178)**	**0.028 (0.126)**	0.042 (0.150)
Average absolute mispricing[a]	**0.138 (0.128)**	**0.102 (0.078)**	0.117 (0.103)
Average number of futures trades per minute	**1.357 (0.414)**	**2.296 (0.602)**	1.815 (0.696)
Average days to maturity	**48.22 (24.10)**	**56.52 (25.08)**	53.13 (25.02)
Average daily index coefficient of variation (CV)[b]	0.560 (0.300)	0.523 (0.239)	0.542 (0.272)
First-order autocorrelation of mispricing[c]	0.853**	0.837**	0.848**
First-order autocorrelation of mispricing changes[c]	−0.211**	−0.260**	−0.234**

[a]In percentage of the underlying index value.

[b]$CV_t = \frac{100\%}{\overline{S}_t}\sqrt{\frac{\sum_{\tau=1}^{n}(S_\tau - \overline{S}_t)^2}{n-1}}$, where S_τ is the spot index price, $\overline{S}_t$ is the daily average of the index, and n is the number of index observations per trading day.

[c]z-statistic of the test for the difference between first-order autocorrelations for the two subperiods that uses Fisher's Z transformation is significant at the 1% level. The %COMPCORR macro in SAS is used to calculate this statistic.

Standard deviations are in parentheses. **Indicates that the autocorrelation is different from zero at the 1% significance level. Bold text indicates that the linear rank sum z-statistic fo the two-sample test for difference between medians for the two subperiods is significant at the 1% level. This nonparametric test statistic is used because the normality assumptions for the t test are not satisfied. The z-statistic is calculated using the NPAR1WAY procedure in SAS.

declines significantly in the post-Cube period. This finding is consistent with evidence of high autocorrelation in the mispricing time series documented by MacKinlay and Ramaswamy (1988).

Other descriptive statistics show that trading in Nasdaq-100 futures was more active in the second part of the sample period and the number of observations in that period grew by about 45%. This is consistent with the growth rate for the overall market. Also, the average time to expiration of futures contracts in the post-Cube period is somewhat higher. Finally, a calculation of the average daily coefficient of variation of the index shows that there is no statistically significant difference in volatility of the Nasdaq-100 index between the two periods.

Table II presents the frequency of observed (ex post) boundary violations for four levels of transaction cost boundaries. Both the frequency and number of boundary violations decline significantly in the post-Cube period. The frequency rate decline in the post-Cube period grows from 34% at 0.15% transaction cost level to a tenfold decline at the 0.5% level. The absolute number of violations exhibits a similar pattern even though there is an increase in the number of transactions in the later period. These results further support the hypothesis that introduction of Cube trading has tightened the spot-futures pricing relationship.

A similar pattern can be seen in more detail from Figure 1. For every 0.05% increase in futures contract mispricing there is a monotonically increasing percentage difference between frequencies of mispricings in the pre- and post-Cube periods. For example, frequency of mispricings that fall within the 0.15–0.20% interval declines by approximately one-tenth, while frequency of mispricings exceeding 0.50% declines tenfold.

Table II also reveals that most of the observed boundary violations both before and after the introduction of Cubes are in clusters.[13] For example, although the total number of violations of the 0.5% transaction cost boundary in the post-Cube period is only 112, the maximum number of violations of this boundary in one 10-min interval is as high as 22. This result supports earlier findings of persistence in violations reported by Chung (1991). However, both the number of clusters and the average number of violations within the clusters are significantly reduced in the post-Cube period. Furthermore, in the post-Cube period there is a reduction in the percentage of violations at the 0.35% and 0.50% transaction cost levels that are in clusters.

[13]To examine the clustering of boundary violations, each trading day is partitioned into 36 10-min intervals.

TABLE II

Summary Statistics for Ex Post Violations of Futures Price Boundaries by Nasdaq-100 Futures Contracts for July 1, 1998 to October 29, 1999

Time Period	*Number of Observations*	*Transaction Costs*[a]	*Number of Violations*	*Number of Violations as % of Number of Observations*	*Average Number of Violations in 10-min Intervals*[b]	*Maximum Number of Violations in 10-min Intervals*[b]	*Average % of Violations in 10-min Intervals*[b,c]	*% of Violations in Clusters of 5 or More in 10-min Intervals*[b,d]
7/1/98–3/9/99	61,543	0.15	22,322	**36.21%**	6.04	31	**44.68%**	**74.25%**
		0.20	13,616	**22.09%**	4.94	29	**35.72%**	**67.69%**
		0.35	2,778	**4.51%**	3.86	21	**22.75%**	**58.42%**
		0.50	888	**1.44%**	4.14	20	**26.69%**	**68.58%**
3/10/99–10/29/99	89,154	0.15	21,447	**24.06%**	5.90	30	**31.76%**	**76.93%**
		0.20	9,995	**11.21%**	4.32	29	**22.42%**	**64.78%**
		0.35	632	**0.71%**	2.69	26	**12.27%**	**48.26%**
		0.50	112	**0.13%**	2.71	22	**11.67%**	**52.68%**
7/1/98–10/29/99	150,697	0.15	43,769	29.04%	5.96	31	37.25%	75.56%
		0.20	23,611	15.67%	4.61	29	28.56%	66.46%
		0.35	3,410	2.26%	3.48	26	21.39%	56.54%
		0.50	1,000	0.66%	3.82	22	23.33%	66.80%

[a]In percentage of the underlying index value.
[b]In 10-min intervals that contain boundary violations.
[c]Percentage of the number of observations in the same intervals.
[d]Percentage of the total number of violations.
Bold text indicates that the chi-square statistic of the test of the difference between the two subperiods is significant at the 1% level.

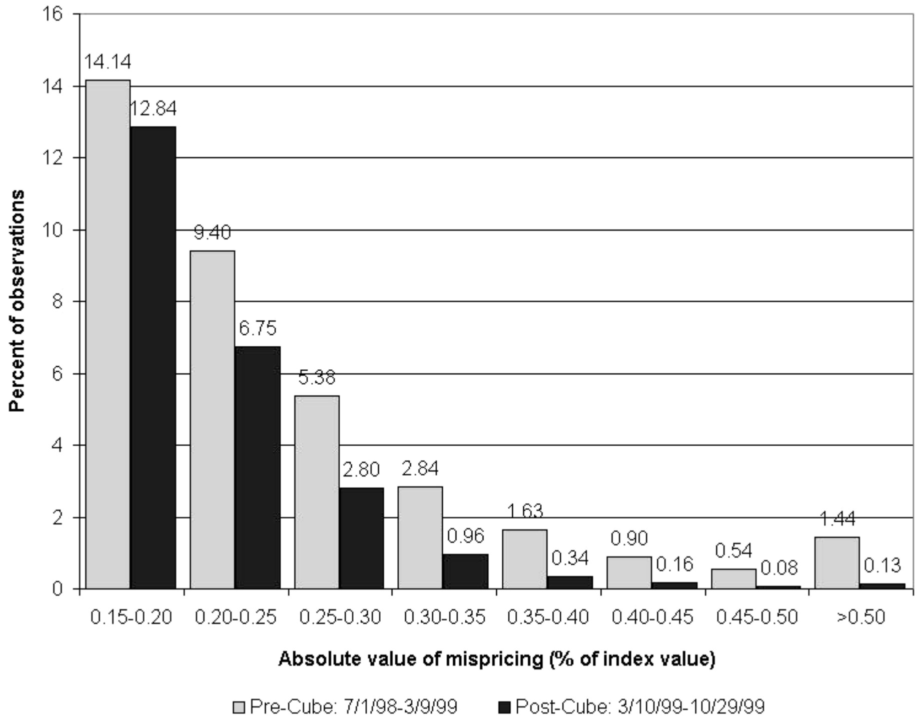

FIGURE 1

Frequency distribution of absolute value of Nasdaq-100 futures mispricing.

Ex Ante Mispricing Results

Table III presents summary statistics for simulated arbitrage trades in the Nasdaq-100 futures contracts for several levels of transaction costs and execution lags. The results are consistent with Hypothesis 2 that ex ante violations (profitable trades) become less frequent after the introduction of Cubes. Not only is the number of ex ante violations reduced in the post-Cube period relative to the pre-Cube period, but the percentage of ex post violations that remain ex ante also appears to be smaller. This result holds for all levels of transaction costs above 0.15% and for all execution lags. For example, Panel B shows that only 44 ex ante violations, which is 39% of the ex post sample for 0.5% transaction costs and 1-min execution lag, are observed in the post-Cube period compared to 497 ex ante violations which is 56% of the ex post sample in the pre-Cube period. The results from Table III reveal that the average size of the mispricing signal, i.e., the positive difference between mispricing and transaction costs falls in the post-Cube period. The table also shows that, on average, simulated arbitrage trades are profitable in the pre-Cube period. This realized profit turns into a realized loss in the post-Cube period for all levels of transaction costs above 0.15% as well as for all three execution lags. Finally, Table III reports a significant

TABLE III

Summary Statistics for Simulated Arbitrage Trades for Nasdaq-100 Futures Contracts for July 1, 1998 to October 29, 1999

Time Period	*Transaction Costs*[a]	*Number of Trades*[b]	*Profitable Trades*	*Profitable Trades as % of All Trades*	*Average Signal*[a]	*Average Profit*[a]	*Correlation of Signal and Profit*[c]
Panel A: 30-s Execution Lag							
7/1/98–3/9/99	0.15	22,222	14,773	**66.48%**	0.106**	0.063**	0.730**
	0.20	13,540	8,192	**60.50%**	0.109**	0.055**	0.744**
	0.35	2,765	1,509	**54.58%**	0.171**	0.083**	0.768**
	0.50	884	553	**62.56%**	0.269**	0.163**	0.738**
3/10/99–10/29/99	0.15	21,345	12,425	**58.21%**	0.062**	0.018**	0.472**
	0.20	9,942	4,729	**47.57%**	0.057**	−0.001	0.472**
	0.35	628	247	**39.33%**	0.101**	−0.015*	0.443**
	0.50	112	49	**43.75%**	0.201**	−0.017	0.269**
7/1/98–10/29/99	0.15	43,567	27,198	62.43%	0.084**	0.041**	0.687**
	0.20	23,489	12,921	55.01%	0.087**	0.031**	0.712**
	0.35	3,393	1,756	51.75%	0.158**	0.065**	0.747**
	0.50	996	602	60.44%	0.262**	0.143**	0.713**
Panel B: 1-min Execution Lag							
7/1/98–3/9/99	0.15	22,172	13,751	**62.02%**	0.106**	0.050**	0.666**
	0.20	13,513	7,556	**55.92%**	0.109**	0.040**	0.683**
	0.35	2,761	1,352	**48.97%**	0.171**	0.055**	0.710**
	0.50	883	497	**56.29%**	0.269**	0.122**	0.682**
3/10/99–10/29/99	0.15	21,286	11,040	**51.87%**	0.062**	0.004**	0.400**
	0.20	9,913	4,046	**40.82%**	0.057**	−0.018**	0.400**
	0.35	624	189	**30.29%**	0.101**	−0.049**	0.427**
	0.50	112	44	**39.29%**	0.201**	−0.038	0.210*
7/1/98–10/29/99	0.15	43,458	24,791	57.05%	0.084**	0.028**	0.623**
	0.20	23,426	11,602	49.53%	0.087**	0.015**	0.651**
	0.35	3,385	1,541	45.52%	0.158**	0.036**	0.694**
	0.50	995	541	54.37%	0.262**	0.104**	0.660**
Panel C: 2-min Execution Lag							
7/1/98–3/9/99	0.15	22,071	12,291	**55.69%**	0.106**	0.030**	0.556**
	0.20	13,456	6,564	**48.78%**	0.109**	0.014**	0.569**
	0.35	2,754	1,095	**39.76%**	0.171**	−0.001	0.602**
	0.50	881	378	**42.91%**	0.269**	0.030*	0.583**
3/10/99–10/29/99	0.15	21,166	9,497	**44.87%**	0.062**	−0.015**	0.307**
	0.20	9,855	3,356	**34.05%**	0.057**	−0.041**	0.299**
	0.35	622	136	**21.86%**	0.101**	−0.102**	0.371**
	0.50	112	31	**27.68%**	0.201**	−0.115**	0.269**
7/1/98–10/29/99	0.15	43,237	21,788	50.39%	0.084**	0.008**	0.515**
	0.20	23,311	9,920	42.56%	0.087**	−0.009**	0.539**
	0.35	3,376	1,231	36.46%	0.158**	−0.020**	0.590**
	0.50	993	409	41.19%	0.262**	0.013	0.571**

[a]In percentage of the underlying index value.
[b]The number of trades is slightly lower than the number of violations because a small number of violations occur during the last 1 or 2 minutes of trading and arbitrage trades cannot be executed on the same day.
[c]*z*-statistic of the test for the difference between correlations for the two subperiods that uses Fisher's *Z* transformation is significant at the 1% level.
Mispricing signal (expected profit) is the difference between the absolute value of ex post mispricing exceeding a chosen transaction costs boundary and that boundary. Simulated arbitrage trades are triggered by mispricing signals and executed after a lag. Profitable trades (ex ante violations) are simulated trades that result in positive ex ante (realized) profits.
**, *Indicate that the *t*-statistic of the test of difference from zero is significant at the 1% and 5% levels, respectively. Bold text indicates that the chi-square statistic of the test of the difference between the two subperiods is significant at the 1% level.

decline in the correlation between mispricing signal and realized profit. This finding supports the conclusion that in the post-Cube period the market reacts faster to observed mispricings.

Relating the findings reported in Table III to the previously discussed results showing persistence in violations, one can say that simulated arbitrage trades become much riskier in the post-Cube period for two reasons. First, although boundary violations still show serious persistence, their magnitude is reduced and second, the relative frequency of subsequent violations falls. These results lend further evidence that the introduction of Cubes has reduced the effective transaction costs needed to form the spot-futures market arbitrage portfolio.

Regression Results

Inferences on improvements in Nasdaq-100 futures pricing efficiency after introduction of Cubes could be affected by changes in market volatility over the sample period. Although, as reported in Table I, the average Nasdaq-100 index volatility was about the same in both subperiods, periods of high volatility may have existed in the pre-Cube period. One could argue that there should be more violations of transaction cost boundaries during periods of high index volatility. Higher volatility makes arbitrage riskier by increasing uncertainty of arbitrage profits. It is reasonable to expect that when this risk is high enough, arbitrage trades will not be initiated even when they appear profitable, as arbitrageurs wait for even larger mispricing that serves as a "buffer" against risk. Therefore, it may take longer for even relatively high mispricing to be eliminated by arbitrage. Yadav and Pope (1994) show that futures mispricing tends to be higher during periods of high index volatility. However, it is also possible that higher volatility leads to a tighter spot-futures pricing relationship by inviting more arbitrage services. Chan and Chung (1993) provide evidence to support this notion. They demonstrate that increases in futures mispricing are followed by increases in volatility of cash and futures prices and the mispricing subsequently declines.

Furthermore, changes in futures trading volume also can affect the spot-futures pricing relationship. Recall that Table I shows a significant increase in futures trading frequency in the post-Cube period. As such, any inference must control for these effects to be reliable and so the dummy variable based regression defined in equation (4) may be estimated. The coefficient of variation is used as a proxy for the spot volatility and the number of futures trades per minute is used as a proxy for futures volume.[14] The

[14]Jones, Kaul, and Lipson (1994) show that number of trades contains most of the information important for describing trading activity.

TABLE IV
Estimates of Daily Average Absolute Mispricing Regression*

	β_0	β_1	β_2	β_3	β_4	φ_1	φ_2	φ_3	φ_4
Value of coefficient	0.021	−0.105	0.038	0.002	0.010	0.166	0.188	0.102	0.099
t-statistic	2.18	−2.47	4.07	0.43	2.80	2.78	3.37	2.14	2.04
p-value	0.0295	0.0133	0.0001	0.6678	0.0051	0.0055	0.0007	0.0327	0.0412

*$|x_t| = \beta_0 + \beta_1 D_t + \beta_2 CV_t + \beta_3 FT_t + \beta_4 ET_t + \sum_{i=1}^{4}\varphi_i |x_{t-i}| + \varepsilon_t$, where $|x_t|$ is the daily average of absolute mispricing, D_t is a dummy variable that equals 0 during the pre-Cube period and 1 afterwards, CV_t is daily coefficient of variation of the spot index, FT_t is daily number of futures trades divided by the number of minutes in each particular trading day, and ET_t is time to expiration of the futures contract divided by the average time to expiration for the sample period. $N = 332$. Total $R^2 = 0.5129$.
x_t observations are winsorized at the 99th percentile to reduce the influence of outliers.
Test of the null hypothesis that the residuals are white noise: $\chi^2 = 2.17$, *p*-value = 0.904. Test of the null hypothesis that the squared residuals are white noise: $\chi^2 = 9.99$, *p*-value = 0.174. This Ljung–Box chi-square statistic is computed using autocorrelations of six residuals.

TABLE V
Estimates of Daily Number of Boundary Violations Regression*

	β_0	β_1	β_2	β_3	β_4	φ_1	φ_2	φ_3	φ_4
Value of coefficient	−9.455	−4.568	11.767	4.258	3.805	0.160	0.130	0.086	0.076
t-statistic	−6.12	−4.62	4.47	4.20	4.48	2.86	2.25	1.99	1.85
p-value	0.0001	0.0001	0.0001	0.0001	0.0001	0.0042	0.0245	0.0461	0.0641

*$V_t = \beta_0 + \beta_1 D_t + \beta_2 CV_t + \beta_3 FT_t + \beta_4 ET_t + \sum_{i=1}^{4}\varphi_i V_{t-i} + \varepsilon_t$, where V_t is the number of ex post futures price violations of the 0.2% transaction cost boundary divided by the number of hours in each particular trading day, D_t is a dummy variable that equals 0 during the pre-Cube period and 1 afterwards, CV_t is daily coefficient of variation of the spot index, FT_t is daily number of futures trades divided by the number of minutes in each particular trading day, and ET_t is time to expiration of the futures contract divided by the average time to expiration for the sample period.
$N = 332$. Total $R^2 = 0.4613$.
V_t observations are winsorized at the 99th percentile to reduce the influence of outliers.
Test of the null hypothesis that the residuals are white noise: $\chi^2 = 2.07$, *p*-value = 0.913. Test of the null hypothesis that the squared residuals are white noise: $\chi^2 = 8.76$, *p*-value = 0.187. This Ljung–Box chi-square statistic is computed using autocorrelations of six residuals.

results of the QML estimation are reported in Table IV. While the results suggest that there is a significant positive relationship between index volatility and absolute mispricing, the coefficient for the dummy variable representing the change in mispricing in the post-Cube period remains negative and significant, indicating a decrease in average absolute value of mispricing in the post-Cube period.

Results of the QML estimation of equation (6) reported in Table V show a significant reduction in the frequency of ex post violations of the 0.2% futures price boundary in the post-Cube period. The results show a significant positive relationship between the frequency of futures trading and the number of futures price boundary violations. The positive association between price volatility and trading volume is widely documented

TABLE VI
Tobit Estimates of Ex Ante-Ex Post Ratio Regression*

	β_0	β_1	β_2	β_3	β_4
Value of coefficient	0.017	−0.125	0.314	−0.029	0.171
z-statistic	0.367	−3.202	8.166	−1.055	7.033
p-value	0.7139	0.0014	0.0001	0.2916	0.0001

*$APR_t = \beta_0 + \beta_1 D_t + \beta_2 CV_t + \beta_3 FT_t + \beta_4 ET_t + \varepsilon_t$, where APR_t is the number of ex ante futures price violations of the 0.2% transaction cost boundary (calculated with the execution lag of 2 minutes) in each particular trading day divided by the number of ex post violations of the same boundary that occurred during the same day, D_t is a dummy variable that equals 0 during the pre-Cube period and 1 afterwards, CV_t is daily coefficient of variation of the spot index, FT_t is daily number of futures trades divided by the number of minutes in each particular trading day, and ET_t is time to expiration of the futures contract divided by the average time to expiration for the sample period.
$N = 335$. Total $R^2 = 0.3202$ (from ordinary least squares regression).

(see, e.g., Karpoff, 1987). Since the futures volatility is positively related to the number of violations, the observed positive relationship between the frequency of futures trading and the number of violations can be expected. The large fall in frequency of boundary violations in the post-Cube period occurred despite the large growth in the futures trading volume. This finding lends further support to the hypothesis that the reduction in the frequency of futures price boundary violations found in the post-Cube period is a function at least in part of the introduction of the tracking stock.

Table VI shows the results of the Tobit estimation of equation (7). A significant reduction in the number of ex ante violations of 0.2% transaction cost boundary as percentage of the number of ex post violations of the same boundary in the post-Cube period is evident. Combined with evidence reported in Table III, this result shows that the apparent violations of transaction cost boundaries are eliminated faster in the post-Cube period. The estimates of the coefficient of the time to maturity variable in equations (4), (6), and (7) are positive and highly significant. This result supports earlier observations of MacKinlay and Ramaswamy (1988), Klemkosky and Lee (1991), and Yadav and Pope (1994), who show that the magnitude of mispricing tends to increase on average with maturity of the futures.

Results for Reduced Short Selling Restrictions

The preceding sections show that both ex post and ex ante futures price boundary violations become less frequent after the introduction of Cubes. This section discusses testing Hypothesis 3 that easing of short-sale restrictions with introduction of Cubes reduced the relative frequency of violations of the lower arbitrage boundaries. The results for

TABLE VII

Summary Statistics for Simulated Long and Short Arbitrage Trades for July 1, 1998 to October 29, 1999

		Long Arbitrage Trades			*Short Arbitrage Trades*		
Time Period	*Transaction Costs*[a]	*% of All Trades*	*% Profitable*	*Correlation of Signal and Profit*	*% of All Trades*	*% Profitable*	*Correlation of Signal and Profit*[b]
Panel A: 30-s Execution Lag							
7/1/98–3/9/99	0.15	**76.29%**	**69.76%**	0.737**	**23.71%**	55.91%	0.711**
	0.20	**78.32%**	**63.40%**	0.748**	**21.68%**	50.02%	0.737**
	0.35	**80.29%**	**55.18%**	0.773**	**19.71%**	**52.11%**	0.757**
	0.50	**76.81%**	61.27%	0.752**	**23.19%**	**66.83%**	0.694**
3/10/99–10/29/99	0.15	**68.18%**	**60.06%**	0.481**	**31.82%**	54.26%	0.465**
	0.20	**66.20%**	**47.37%**	0.500**	**33.80%**	47.95%	0.432**
	0.35	**46.82%**	**37.07%**	0.554**	**53.18%**	**41.32%**	0.191**
	0.50	**49.11%**	58.18%	0.258	**50.89%**	**29.82%**	−0.176
7/1/98–10/29/99	0.15	72.32%	65.28%	0.706**	27.68%	54.98%	0.706**
	0.20	73.20%	57.24%	0.728**	26.80%	48.91%	0.675**
	0.35	74.09%	53.06%	0.759**	25.91%	48.01%	0.719**
	0.50	73.69%	61.04%	0.725**	26.31%	58.78%	0.682**
Panel B: 1-min Execution Lag							
7/1/98–3/9/99	0.15	**76.28%**	**66.13%**	0.677**	**23.72%**	48.80%	0.641**
	0.20	**78.33%**	**59.37%**	0.690**	**21.67%**	43.44%	0.671**
	0.35	**80.30%**	**49.75%**	0.715**	**19.70%**	**45.77%**	0.700**
	0.50	**76.78%**	54.72%	0.702**	**23.22%**	**61.46%**	0.618**
3/10/99–10/29/99	0.15	**68.19%**	**53.80%**	0.409**	**31.81%**	47.72%	0.397**
	0.20	**66.21%**	**40.61%**	0.427**	**33.79%**	41.22%	0.366**
	0.35	**46.79%**	**28.77%**	0.508**	**53.21%**	**31.63%**	0.239**
	0.50	**49.11%**	52.73%	0.170	**50.89%**	**26.32%**	−0.127
7/1/98–10/29/99	0.15	72.32%	60.44%	0.645**	27.68%	48.19%	0.574**
	0.20	73.20%	52.19%	0.671**	26.80%	42.26%	0.609**
	0.35	74.12%	47.31%	0.702**	25.88%	40.41%	0.675**
	0.50	73.67%	54.57%	0.677**	26.33%	53.82%	0.614**
Panel C: 2-min Execution Lag							
7/1/98–3/9/99	0.15	**76.28%**	**60.38%**	0.565**	**23.72%**	40.59%	0.535**
	0.20	**78.32%**	**52.75%**	0.575**	**21.68%**	34.45%	0.568**
	0.35	**80.25%**	**40.77%**	0.605**	**19.75%**	**35.66%**	0.608**
	0.50	**76.73%**	42.01%	0.606**	**23.27%**	**45.85%**	0.524**
3/10/99–10/29/99	0.15	**68.19%**	**46.70%**	0.324**	**31.81%**	40.95%	0.295**
	0.20	**66.20%**	**33.80%**	0.336**	**33.80%**	34.55%	0.253**
	0.35	**46.62%**	**21.72%**	0.433**	**53.38%**	**21.99%**	0.215**
	0.50	**49.11%**	45.45%	0.223	**50.89%**	**10.53%**	−0.021
7/1/98–10/29/99	0.15	72.32%	54.07%	0.538**	27.68%	40.79%	0.466**
	0.20	73.20%	45.50%	0.559**	26.80%	34.51%	0.499**
	0.35	74.05%	38.56%	0.595**	25.95%	30.48%	0.589**
	0.50	73.62%	42.27%	0.588**	26.38%	38.17%	0.532**

[a]In percentage of the underlying index value.

[b]*z*-statistic of the test for the difference between correlations for the two subperiods that uses Fisher's *Z* transformation is significant at the 1% level.

Mispricing signal (expected profit) is the difference between the absolute value of ex post mispricing exceeding a chosen transaction costs boundary and that boundary. Simulated arbitrage trades are triggered by mispricing signals and executed after a lag. Profitable trades (ex ante violations) are simulated trades that result in positive ex ante (realized) profits. Long arbitrage trades are recorded when futures price exceeds the upper transaction costs boundary and short arbitrage trades are recorded when futures price falls below the lower transaction costs boundary. Bold text indicates that the chi-square statistic of the test of the difference between the two subperiods is significant at the 1% level.

simulated long and short arbitrage trades for given levels of transaction costs and execution lags are reported in Table VII. In the pre-Cube period a higher frequency of violations for long arbitrages are observed relative to the post-Cube period. This finding is similar to the higher frequency of simulated long arbitrages reported by Chung (1991). Moreover, in direct contradiction to Hypothesis 3, the relative frequency of "short" violations increases after the introduction of Cubes. For example, while simulated short arbitrage trades with the 0.35% transaction cost threshold and 1-min execution lag account for only 20% of the total number of trades in the pre-Cube period, this proportion grows to 53% in the post-Cube period.

While the relative frequency of short violations increases in the second period, the percentage of profitable short arbitrage trades for higher transaction cost levels declines. Also, the correlation between mispricing signals and realized profits for short arbitrages in the post-Cube period is reduced relative to the pre-Cube period. This correlation even becomes insignificant at the 0.5% transaction cost level. This implies that short ex post violations are eliminated faster. However, this is also the case for long violations, although the percentage of profitable long arbitrages does not decline for the 0.5% transaction cost level.

The results reported in Table VII show that elimination of the downtick rule restriction on short sales with introduction of Cubes had little impact on effective transaction costs of short arbitrage trades. However, these findings support the discussion by Neal (1996), which suggests that institutional traders can avoid the short-sale restrictions by using direct sales. Therefore, the results imply that the significant reduction in the frequency of boundary violations is primarily a function of lower transaction costs, shorter arbitrage lags, and the reduction of tracking risk.

CONCLUSION

This paper examines changes in the Nasdaq-100 index futures pricing efficiency after the introduction of Cubes. Using tick-by-tick futures transactions and index value data, this paper calculates ex post and ex ante violations of futures price boundaries. The findings indicate that both the average magnitude of futures mispricing and the frequency of boundary violations fall after the introduction of Cubes. Boundary violations that do occur in the post-Cube period are eliminated faster. This result is observed across several levels of transaction costs and execution lags. Furthermore, the findings cannot be explained by changes in futures trading activity or index volatility. The reported improvement in Nasdaq-100 futures pricing efficiency is attributed at least in part to the increased ease in establishing a spot Nasdaq-100 index position after the introduction of Cubes.

The reduction of ex post and ex ante violations is observed to be independent of the time to maturity of futures contracts. Consistent with earlier findings, there is a tendency for the magnitude of mispricing signal and frequency of boundary violations to increase with time to maturity. This paper also finds significant clustering of boundary violations before and after introduction of Cubes. However, the frequency of clusters, relative frequency of violations within the clusters, and the percentage of violations that are in clusters are reduced in the post-Cube period. Finally, the results indicate that the relative frequency of simulated short arbitrage trades increases in the post-Cube period. This suggests that the reported improvements in the Nasdaq-100 index futures pricing efficiency are not related to easing of short-sale restrictions with introduction of Cubes.

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