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The Flash Crash: An Examination of Shareholder Wealth and Market Quality

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The Flash Crash: An Examination of Shareholder Wealth and Market Quality

Abstract

We investigate stock returns, market quality, and options market activity around the flash crash of May 6, 2010. Abnormal returns are negative on the day of and the day after the flash crash for stocks that had trades that executed during the crash subsequently cancelled by either Nasdaq or NYSE Arca. Consistent with studies that suggest that other sources of liquidity withdrew from the markets during the flash crash, we find that the fraction of trades executed by the NYSE increases during this volatile period. Market quality deteriorates following the flash crash as bid-ask spreads increase and quote depths decrease. Evidence from the options markets indicates that investor uncertainty increased around the time of the crash and remained elevated for several days afterwards.

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1. Introduction

On May 6, 2010, the Dow Jones Industrial Average (DJIA) opened at 10,862.30 and closed at 10,517.83. Not captured in this 3.2 percent loss are the specifics of one of the most tumultuous days in U.S. stock market history. Fig. 1, which reports the price performance of the SPDR Dow Jones Industrial Average ETF, illustrates the dramatic events of the day. After creeping slowly downward following the market's open, the DJIA began a rapid decline at around 2:30 p.m. that ultimately shaved nearly 1,000 points off of the index. However, the decline was short-lived as things quickly reversed course, leading to an equally rapid recovery. A number of individual stocks also experienced harrowing, but brief, price shocks. For example, shares of The Procter & Gamble Company, which traded at over $60/share at 2:40 p.m., fell to $39.37/share in approximately 3.5 minutes, only to bounce back above $60/share about a minute later. Of the 30 DJIA components, 18 experienced price declines of at least 5 percent between 2:40 p.m. and 2:50 p.m., and the remaining 12 fell by at least 2.3 percent. Due to their sudden and dramatic nature, the events of May 6, 2010 are often referred to as the 'flash crash.'

<<FIG. 1 ABOUT HERE>>

Regulators, researchers, and other market participants continue to seek explanations for that day's events. Within two weeks of the flash crash, the U.S. Commodity Futures Trading Commission (CFTC) and the U.S. Securities & Exchange Commission (SEC) jointly issued a report that proposed a number of contributing factors, including the linkage between ETFs and E-mini S&P 500 futures and individual securities; mismatches in liquidity; disparate trading

conventions among various exchanges; stub quotes; and market and limit orders.[1] The report places particular emphasis on the impact of an unusually large sell order in E-mini S&P 500 futures contracts. Academic studies of the flash crash tend to focus on the role of high frequency traders. While stopping short of blaming high frequency traders directly, Easley et al. (2011) and Kirilenko et al. (2011) conclude that they did contribute to the extreme market volatility witnessed on the day of the crash. Lee et al. (2011) suggest that the flash crash resulted from systematic traders with similar trading strategies, while Yu (2011) finds evidence that contrarian trading strategies helped to mitigate the effects of the flash crash.

We contribute to the search for answers by studying NYSE-listed stocks that had trades executed during the flash crash that were subsequently cancelled by either Nasdaq or NYSE Arca and a closely matched sample of stocks that did not experience cancelled trades. The focus of our analysis is fourfold. First, we examine stock returns around the flash crash. Second, we provide details on the allocation of trading volume across trading venues during this period of extreme volatility. Third, we examine market quality before, during, and after the flash crash, including measures of bid-ask spreads and quote depth. Fourth, for sample stocks with tradable options, we study changes to the sensitivity of option prices to quantifiable risk factors around the flash crash.

We find that shareholder wealth declined significantly in the days surrounding the flash crash. The average cumulative abnormal return over the two days beginning on the day of the flash crash is –1.77 percent for stocks that had trades that executed on May 6, 2010 that were

[1] U.S. Commodity Futures Trading Commission (CFTC) and U.S. Securities and Exchange Commission (SEC), "Findings Regarding the Market Events of May 6, 2010", report filed September 30, 2010. Available online at http://www.sec.gov/news/studies/2010/marketevents-report.pdf. Henceforth referred to as CFTC-SEC (2010).

subsequently cancelled. During the flash crash, several of our sample stocks had trades execute at stub quotes (e.g., $0.01 or $100,000), which indicates that the limit order book was very thin, particularly on the bid side.[2] One possibility is that these trades may have accelerated price discovery and contributed to the observed price declines.[3] Deteriorating market quality also may have been a contributing factor, as prior research finds that liquidity and stock returns are positively correlated (see, for example, Amihud and Mendelson, 1986). However, we find that returns are not significantly different from zero over the same period for a closely matched sample of stocks that did not have cancelled trades, despite the fact that these stocks also experienced a negative, albeit less severe, liquidity shock around the flash crash.

Consistent with prior studies that suggest that other sources of liquidity withdrew during the flash crash, we find that the fraction of trades executed on the NYSE increased significantly on the day of the crash. We find that bid-ask spreads increased and quote depth decreased in the wake of the flash crash for both the base and matched sample stocks, although the effects are more pronounced for stocks with cancelled trades. While it is difficult to attribute the deterioration in market quality directly to the flash crash, such events have the potential to negatively affect investor confidence, stock market participation, and liquidity. Contemporaneous events are also likely to have contributed to investor uncertainty during this period. For example, the CFTC-SEC (2010) report notes that premiums on credit default swaps

[2] CFTC-SEC (2010) defines stub quotes as "quotes generated by market makers (or exchanges on their behalf) at levels far away from the current market in order to fulfill continuous two-sided quoting obligations even when a market maker has withdrawn from active trading" (p. 5). According to the CFTC-SEC, of the 5.5 million shares traded that were ultimately cancelled, nearly two-thirds were executed at a price of less than $1.00.

[3] Madhavan (2012) and McInish et al. (2012) also conjecture that depleted limit order books contributed to the flash crash.

increased for a number of European sovereign debt securities and the Euro fell in global currency markets on May 6, 2010. Increased investor uncertainly is also evident in the options markets. We find that implied volatility increased dramatically and the sensitivity of option prices to changes in the underlying stock prices (gamma) and implied volatility (vega) were noticeably different following the flash crash.

Whereas prior studies of the flash crash tend to focus on exchange traded funds that track broad stock market indices, ours is one of the first to examine individual stocks impacted by the crash.[4] This approach makes it possible to measure changes in shareholder wealth and the underlying market quality of stocks in the days surrounding the flash crash. We find that the shareholder wealth, market quality, and option market effects are perceptible well beyond May 6, 2010. These effects are not only apparent for stocks that were singled out for trade cancellations by the exchanges, but also for matched samples that did not experience cancelled trades.

The remainder of this study is organized as follows. In Section 2, we describe our sample and methodology. We report our empirical findings in Section 3 and conclude in Section 4.

2. Sample selection

Our base sample consists of the common stocks of 29 NYSE-listed firms incorporated in the U.S. that had trades executed on May 6, 2010 and subsequently cancelled by either Nasdaq or NYSE Arca. Nasdaq and NYSE Arca cancelled all trades that occurred between 2:40 p.m. and 3:00 p.m. and were executed at a price that was 60 percent higher or lower than the last trade that

[4] The aforementioned paper by Yu (2011) examines the impact of contrarian trading on the magnitude of individual stock crashes on May 6, 2010.

took place at 2:40 p.m. (or immediately prior).[5] We match each base sample stock with a stock that did not have trades cancelled, using market capitalization, share price, daily turnover (shares traded as a percentage of shares outstanding), and return volatility (standard deviation of daily returns) as the basis of the match. Because of the suspected role of S&P 500 E-mini futures and statistical arbitrage in the flash crash, base sample stocks that are part of the S&P 500 index as of April 1, 2010 are matched with other S&P 500 components. Market capitalization is measured as of April 30, 2010, while share price, daily turnover, and return volatility are averaged over the period April 1, 2010 through April 30, 2010. The match for each base sample stock is the NYSE-listed common stock that minimizes the following expression:

$$Distance = \sum_{i=1}^{4} \left[\frac{factor_i - factor_i^{matched}}{\left(factor_i + factor_i^{matched} \right)/2} \right]^2, \tag{1}$$

where $factor_i$ denotes the value of the i^{th} matching variable for the base sample stock and $factor_i^{matched}$ denotes the value of the i^{th} matching variable for the matched stock. For each matching characteristic, i, this minimization is done subject to the constraint:

$$\left| \frac{factor_i - factor_i^{matched}}{\left(factor_i + factor_i^{matched} \right)/2} \right| < 1. \tag{2}$$

We report the stocks contained in both the base and matched samples in Table 1.

<<TABLE 1 ABOUT HERE>>

In Table 2 we report descriptive statistics for both samples. We report that the typical base sample stock has a market capitalization of over $25 billion, a share price of $40.70, daily

[5] NYSE Euronext did not cancel any trades executed on May 6, 2010. The lists of stocks with trades cancelled by Nasdaq and NYSE Arca are available through the following websites:

http://s.wsj.net/public/resources/documents/st_canceled0507_20100507.html

http://s.wsj.net/public/resources/documents/st_canceledNYSE0507_20100507.html

turnover of 1.06%, and return volatility of 1.77%. Paired *t*-tests indicate that the means of the base and matched samples are not significantly different from one another for any of the four matching characteristics. The median values confirm the suitability of our matched sample. Wilcoxon rank sum tests indicate that the only significant difference in the medians of the base and matched samples is for the market capitalization measure.

<<TABLE 2 ABOUT HERE>>

3. Empirical results

3.1. Abnormal returns

We begin our analysis with an examination of stock returns around the flash crash. Our benchmark for measuring abnormal returns is the Fama-French (1993) three-factor model augmented by Carhart's (1997) momentum factor.[6] The model is:

$$R_{jt} = \alpha_j + \beta_j R_{mt} + s_j SMB_t + h_j HML_t + u_j UMD_t + \varepsilon_{jt}, \quad (3)$$

where R_{jt} is the return on the j^{th} stock on day t, R_{mt} is the return on the market index on day t, SMB_t is the average return on small-firm stocks minus the average return on large-firm stocks on day t, HML_t is the average return on high book-to-market stocks minus the average return on low book-to-market stocks on day t, and UMD_t is the average return on high prior return portfolios minus the average return on low prior return portfolios. β_j, s_j, h_j, and u_j measure a stock's sensitivity to the market, size, book-to-market, and momentum factors, respectively.

Daily abnormal returns are measured for common stock j on day t as:

$$AR_{jt} = R_{jt} - (\hat{\alpha}_j + \hat{\beta}_j R_{mt} + \hat{s}_j SMB_t + \hat{h}_j HML_t + \hat{u}_j UMD_t), \quad (4)$$

[6] Unreported tests confirm that the event study results are robust to alternative benchmarks for measuring abnormal returns, including the market model and a three-factor model that excludes Carhart's (1997) momentum factor.

where $\hat{\alpha}_j, \hat{\beta}_j, \hat{s}_j, \hat{h}_j,$ and $\hat{u}_j$ are the Ordinary Least Squares (OLS) estimates from Eq. (3). We estimate Eq. (3) over the 255 trading days ending at least 46 days before the flash crash and calculate abnormal returns for each stock with Eq. (4).

In Table 3, we report the results of our abnormal return analysis. We report mean abnormal returns and the percentage of returns greater than zero for both the base and matched samples for the 11 trading days centered on the day of the flash crash. At the bottom of Table 3 we report cumulative abnormal returns over three windows beginning on the event day. On the day of the flash crash, the abnormal return for the typical base sample stock is –0.80 percent. Over the window [0, +1], the mean cumulative abnormal return is –1.77 percent. The majority of the base sample stocks experience non-positive abnormal returns both on the day of the flash crash (72 percent) and over the two day window beginning on the day of the flash crash (82 percent). Returns for the matched sample are not significantly different from zero over the same period.

<<TABLE 3 ABOUT HERE>>

These results show that the flash crash was accompanied by a significant decline in shareholder wealth, particularly for stocks that subsequently had trades cancelled. The decline in shareholder wealth is consistent with a number of possible explanations. During the flash crash, several of the base sample stocks had trades execute at stub quotes (e.g., $0.01), which indicates that the limit order book was very thin on the bid side. One possibility is that market participants updated their views about these stocks' true value based on this information, leading to the observed price declines. We are not the first to propose that the limit order book played a role in the flash crash. For instance, Madhavan (2012) conjectures that market fragmentation contributed to the flash crash, in part, by thinning out limit order books. McInish et al. (2012)

find evidence that intermarket sweep orders may have destabilized the market by depleting the limit order book.

Another possibility is that the price declines resulted from negative shocks to liquidity, which Amihud and Mendelson (1986) find is positively correlated with stock returns. We report evidence that liquidity deteriorated around the flash crash in subsequent tests. However, despite our finding that returns are not significantly different from zero for the matched sample, we find that market quality deteriorated for both samples around the flash crash. Before turning to market quality and the options markets, we continue with a brief look at trade execution before, during, and after the flash crash.

3.2. Trade execution

Whereas high frequency traders are often a significant source of liquidity in the financial markets, Kirilenko et al. (2011) conclude that high frequency traders' behavior on the day of the flash crash exacerbated market volatility. Consistent with this notion, the CFTC-SEC (2010) report on the flash crash finds evidence that some high frequency traders aggressively sold shares during the crash, while others scaled back or stopped trading altogether. An obvious question arises. Who stepped into the void left when other sources of liquidity moved to the sidelines?

The importance of dedicated market makers has been debated for decades. Garbade and Silber (1979) and Grossman and Miller (1988) highlight the advantages of having a market maker obligated to maintain a market. More recent studies by Glosten (1994) and Bloomfield et al. (2005) suggest, however, that market structure is likely to evolve in favor of public liquidity providers. In Figs. 2a and 2b, we provide evidence that the importance of NYSE designated market makers increased during the flash crash.

<<FIG. 2 ABOUT HERE>>

In Fig. 2a, we report the percentage of trades executed on the NYSE between 9:30 a.m. and 4:00 p.m. for the 21 trading days centered on May 6, 2010. This figure shows a pronounced spike in the percentage of trades executed on the NYSE for both the base and matched samples beginning on the day of the flash crash. Both samples experience an increase in the percentage of trades executed on the NYSE of over 20 percent on the day of the flash crash. That is, from May 5 to May 6, 2010 the percentage of trades executed on the NYSE increases from 23.2 percent to 28.5 percent for the base sample and from 23.4 percent to 28.9 percent for the matched sample.

A closer examination indicates that this shift toward the NYSE began right around the time of the flash crash. In Fig. 2b, we partition May 6, 2010 into 20-minute intervals and report the percentage of trades executed on the NYSE for both samples. Just before 1:00 p.m., approximately 26.6 percent (22.3 percent) of the trades in the base sample (matched sample) stocks were executed on the NYSE. By 2:20 p.m., this figure had increased to 28.0 percent (26.0 percent). Remarkably, just prior to the close of the trading day, the percentage of trades executed on the NYSE approached 35.6 percent and 40.0 percent for the base and matched sample, respectively.

In Fig. 3, we examine trading volume across different market centers, as reported by the Trade and Quote Database. We report, in 20-minute intervals, the percentage of total trading volume captured by the NASD ADF/TRF, NYSE, NYSE Arca, NASD, and BATS.[7] Consistent with Fig. 2, we report a significant increase in the percentage of trading volume executed by the NYSE, beginning at about 2:00 p.m. The majority of this increase comes at the expense of the NASD ADF/TRF, where the primary sources of trades are OTC market makers and block

[7] We exclude venues that capture less than 5 percent of total trading volume from Figure 5.

positioners. This is consistent with the notion that OTC market makers, who typically internalize a large portion of the order flow, instead chose to route orders to the exchanges.

<<FIG. 3 ABOUT HERE>>

The dramatic increase in the number of trades executed on May 6, 2010 highlighted in Figs. 4a and 4b, underscores the importance of the NYSE during this period of market instability. Fig. 4a reports the number of trades executed between 9:30 a.m. and 4:00 p.m. for the 21 trading days centered on May 6, 2010. This figure illustrates the significant spike in the number of trades executed on that day. Fig. 4b partitions May 6, 2010 into 20-minute intervals and shows that the number of trades executed began to increase rapidly just prior to the flash crash.

<<FIG. 4 ABOUT HERE>>

Why did the NYSE execute a larger percentage of trades during the flash crash? Prior studies, including Easley et al. (2011), suggest that high frequency traders, a significant source of liquidity in the financial markets, scaled back their trading during the flash crash. If this was indeed the case, the NYSE designated market makers' obligation to maintain a market may have led them to step into the void created by the absence of high frequency traders. Another possibility, supported by Nanex (2010) research, is that NYSE quotes lagged other markets during the flash crash, which allowed arbitrageurs to profit at the expense of the NYSE and drove trading volume to the exchange.

In Fig. 5, we report evidence consistent with Nanex's (2010) contention that delays in quote dissemination increased seller-initiated volume on the NYSE. We use trade direction indicators constructed using a combination of the tick- and quote-test methodology (Lee and Ready, 1991) and find that the percentage of seller-initiated trades spiked on the NYSE in advance of the flash crash and remained at elevated levels through the end of the trading day. However, neither

explanation (high frequency traders, arbitrage trading) accounts for the sustained increase in trades captured by the NYSE in the days following the flash crash. Not only do we find that the NYSE executed a greater portion of trades during the flash crash, but also for several days afterwards.

<<FIG. 5 ABOUT HERE>>

3.3. Market quality

In this section, we examine market quality measures for signs that liquidity deteriorated in the days and weeks surrounding the flash crash. The primary measure of transaction costs in the microstructure literature is the bid-ask spread, which refers to the difference in the prices that a supplier of immediacy stands ready to buy and sell a security. Demsetz (1968) suggests that the bid-ask spread provides compensation to dealers for providing liquidity. We calculate three spread-based measures that are commonly used in the literature. The first is the absolute spread, which is calculated as follows:

$$Absolute\ spread = A_{it} - B_{it}, \tag{5}$$

where A_{it} and B_{it} represent the ask and bid for security i at time t, respectively.

The second measure is the quoted spread, which is calculated as follows:

$$Quoted\ spread = (A_{it} - B_{it})/P_{it} \times 100, \tag{6}$$

where P_{it} represents the trade price for security i at time t. Determinants of the quoted spread include order handling costs (Tinic, 1972), inventory risk (Stoll, 1978), and adverse selection (Copeland and Galai, 1983).

Lee (1993) finds that trades often occur at a price inside or outside the bid and ask quotes. The third measure, the effective spread, reflects this possibility and represents an estimate of the true execution cost for a trader. Following Lee, the effective spread is calculated as follows:

$$Effective\ spread = 2 \times S_{it} \times (P_{it} - M_{it})/M_{it} \times 100, \quad (7)$$

where S_{it} is the trade direction indicator set equal to +1 (–1) for buy (sell) orders and M_{it} is the quote midpoint calculated as the average of the ask and bid prices.

Lee et al. (1993) suggest that market makers who are subject to adverse selection can both increase spreads and reduce depth, where depth refers to the number of shares a market maker is willing to trade at the prevailing bid and ask quotes. Thus, we consider quote depth as an additional measure of market quality. We measure quote depth as the average depth at the prevailing National Best Bid and Offer bid and ask quotes.

$$Quote\ depth = (Depth_{bid} + Depth_{ask})/2, \quad (8)$$

In Table 4, we report the market quality measures for the base sample (Panel A) and matched sample (Panel B) from one day before through one day after the flash crash (May 5 – May 7, 2010). In addition to the measures discussed above, we report turnover (the daily number of shares traded divided by the number of shares outstanding), volume (number of shares traded across all exchanges), and the percentage of trades executed on the NYSE. Because we are interested in market quality changes that anticipate and/or linger beyond the flash crash, we restrict our analysis to between 9:30 a.m. and 2:00 p.m. to avoid contaminating the results with

potentially temporary market quality changes that occurred during the flash crash.[8] Both panels report daily mean values and day-to-day differences.

<<TABLE 4 ABOUT HERE>>

In Table 4, Panel A, we find that spreads widened and depth decreased around the flash crash for base sample stocks. The spread measures indicate that trading costs were significantly higher the day after the flash crash compared to prior days. For example, the average quoted spread for the base sample is over 44 percent higher on May 7, 2010 compared to the day of the flash crash (0.163 percent and 0.113 percent, respectively). Similar results are observed for absolute and effective spreads. Quote depth is dramatically lower the day after the flash crash compared to the day before and the day of the crash.[9] Finally, both average turnover and volume increased dramatically following the flash crash and, as reported earlier, there is a marked increase in the percentage of trades executed on the NYSE that extended to the day after the flash crash. This evidence is consistent with the CFTC-SEC (2010) contention that high trading volume may not imply sufficient market liquidity in times of high volatility.

In Table 4, Panel B, we report a similar deterioration in market quality for the matched sample. As is the case for the base sample, the matched sample stocks exhibit wider spreads and lower depths following the flash crash. This suggests that the market quality deterioration around

[8] In unreported tests, we find that bid-ask spreads spike and quote depths plummet during the 2:20 – 3:00 p.m. period. Spreads decline rapidly after 3:00 p.m., but remain significantly higher than before the flash crash, while depth remains at depressed levels through the end of the day.

[9] In Table 4, we exclude Radian Group Inc. (RDN) and its corresponding match from the quote depth, volume, and turnover analysis. Radian Group Inc. executed a public offering during this period that is likely to have had a significant impact on these measures.

the flash crash was not limited to the stocks that had trades cancelled.[10] In Panel C, we report differences between the base and matched sample for each day. Day-to-day differences in spreads, while not significant on the day prior to the flash crash, increase and become significant on the day of and the day after the flash crash. This indicates that the worsening of liquidity was more pronounced for stocks with cancelled trades.

In Table 5, we report OLS regressions where the dependent variable is the change in spreads from May 5 through May 7, 2010. Base sample is an indicator variable set equal to 1 for stocks that had a trade executed on May 6, 2010 that was subsequently cancelled by the Nasdaq or NYSE Arca and zero for matched sample stocks. Additional control variables include day-to-day changes in intraday volatility, turnover, and price (price inverse). We also interact the indicator variable with each of the control variables to capture their marginal effects for base sample stocks.

<<TABLE 5 ABOUT HERE>>

The first three columns of Table 5 report changes in absolute, quoted, and effective spreads, respectively, from May 5 to May 6, 2010 (Event / Pre-Event). The results indicate that changes in intraday volatility had a significant impact on absolute spreads, but only for the base sample stocks. Recall from Table 4 that spreads increased significantly for both the base and matched samples following the flash crash. The middle (last) three columns of Table 5 examine changes in spreads from May 6 – May 7, 2010 (May 5 – May 7, 2010). We find some evidence that the

[10] In unreported tests, we examine market quality changes for (i) a random control sample, (ii) a matched sample that excludes the S&P 500 index match criteria, and (iii) a matched sample based on March, 2010 market capitalization, share price, average daily turnover, and return volatility. The results are qualitatively similar to those reported in Tables 4-7 and support the notion that the deterioration in market quality around the flash crash extended beyond the stocks that had trades cancelled.

increase in quoted spreads following the crash is negatively correlated with changes in turnover, but this effect is concentrated in matched sample stocks.

In Table 6, we examine market quality over a two-week period following the day of the flash crash (May 7 – May 20, 2010) and compare the spread and depth measures to the two-week period that preceded the crash (April 22 – May 5, 2010). Because we do not include May 6, we extend our analysis to the full trading day (9:30 a.m. to 4:00 p.m.). We report the results for the base (matched) sample in Panel A (Panel B). In Panel A, we report that each of the spread measures were higher over the two-week period that followed the flash crash compared to the two weeks that preceded it. Additionally, quote depth decreased, while turnover and the percentage of trades executed by the NYSE increased in the wake of the flash crash. In Panel B, we report a similar deterioration in market quality for the matched sample. In Panel C, we find that the market quality measures exhibit few significant differences between the two samples both before and after the flash crash.

<<TABLE 6 ABOUT HERE>>

In Table 7, we report OLS regressions where the dependent variable is the change in absolute, quoted, and effective spreads from the two weeks before the flash crash (April 22 – May 5, 2010) through two weeks after the flash crash (May 7 – May 20, 2010). The control variables mirror those reported in Table 5, but are measured over the two weeks before and after the flash crash. The results suggest that the change in absolute spreads is negatively (positively) correlated with changes in turnover (prices). Changes in quoted and effective spreads are positively correlated with changes in intraday volatility around the flash crash.

<<TABLE 7 ABOUT HERE>>

Overall, our analysis indicates that the deterioration in market quality around the flash crash extended to stocks beyond those with cancelled trades. This deterioration is observable well beyond May 6, 2010 as bid-ask spreads are higher and quote depth is lower in the two weeks following the flash crash compared to the two weeks prior to the flash crash for both the base and matched samples. The multivariate results suggest that trading volume (turnover) and volatility were primary determinants of the higher spreads. Contemporaneous events make it difficult to attribute the deterioration in market quality solely to the flash crash. For instance, the sovereign debt crisis in Europe was also likely to have contributed to investor uncertainty (see, for example, CFTC-SEC, 2010). However, events like the flash crash have the potential to negatively affect investor confidence, stock market participation, and liquidity.

3.4. Options markets

The CFTC-SEC (2010) report indicates that, while the disruptions in the options markets were not as severe as those in the equities markets, some options market makers did respond to the day's volatility by widening quotes, reducing depth, and/or withdrawing from the market entirely. In Table 8, we report additional evidence on the options markets around May 6, 2010. We calculate implied volatility, delta, gamma, and vega using option price data from OptionMetrics for the 11 trading days centered on the day of the flash crash, where delta measures the sensitivity of an option's value to changes in the underlying stock price, gamma measures the sensitivity of an option's delta to changes in the stock price, and vega measures the sensitivity of an option's value to changes in the implied volatility. All calculations use historical LIBOR/Eurodollar rates for interest rate inputs, and correctly incorporate discrete dividend

payments. Variables are calculated using at-the-money forward call options with 30 days to expiration.[11]

<<TABLE 8 ABOUT HERE>>

Our analysis of the options markets supports the notion that uncertainty dramatically increased around the flash crash. We find that implied volatility spiked on the day of the flash crash. For example, for base sample stocks with tradable options, the average implied volatility increased from 0.360 to 0.462 from May 5 to May 6, 2010. This represents a statistically significant increase of 28.33 percent. We also report a less pronounced, albeit significant, increase in implied volatility for the matched sample. While the average delta was unchanged, we find that both gamma and vega changed significantly during the flash crash. The decrease in gamma suggests that option prices became less sensitive to changes in the underlying stock prices on the day of the flash crash. The increase in vega suggests that that option prices became more sensitive to changes in implied volatility around the flash crash. Overall, the results indicate that derivatives traders' volatility estimates increased around the flash crash.

4. Conclusion

The flash crash lasted only a short time, but it left an indelible mark on financial markets. The crash has already affected regulatory policy, as the U.S. Securities and Exchange Commission recently approved trading pauses for individual stocks that experience a price movement of 10 percent or more over a five-minute period.[12] Regulators, researchers, and other

[11] In unreported tests, we examine implied volatility, delta, gamma, and vega using put option data. The results obtained are qualitatively similar to the results reported in Table 8.

[12] Securities and Exchange Commission Act Release no. 34-62252/ June 10, 2010.

market participants continue to seek explanations for the day's events. We contribute to the search for answers by studying stock returns, market quality, and options market activity around the flash crash.

We find that shareholder wealth declined for stocks that had trades that executed on May 6, 2010 that were subsequently cancelled by either Nasdaq or NYSE Arca. We find that the fraction of trades executed on the NYSE increased dramatically during the flash crash and that market quality deteriorated, as bid-ask spreads increased and quote depths decreased. We also report significant changes in the derivatives markets as implied volatility increased, and option values became less (more) sensitive to changes in the underlying stock prices (implied volatility). These effects were not limited to stocks with cancelled trades but are also evident for a closely matched sample of stocks without trade cancellations. While it is difficult to attribute all of the results that we document strictly to the flash crash, such events have the potential to negatively impact investor confidence and destabilize financial markets.

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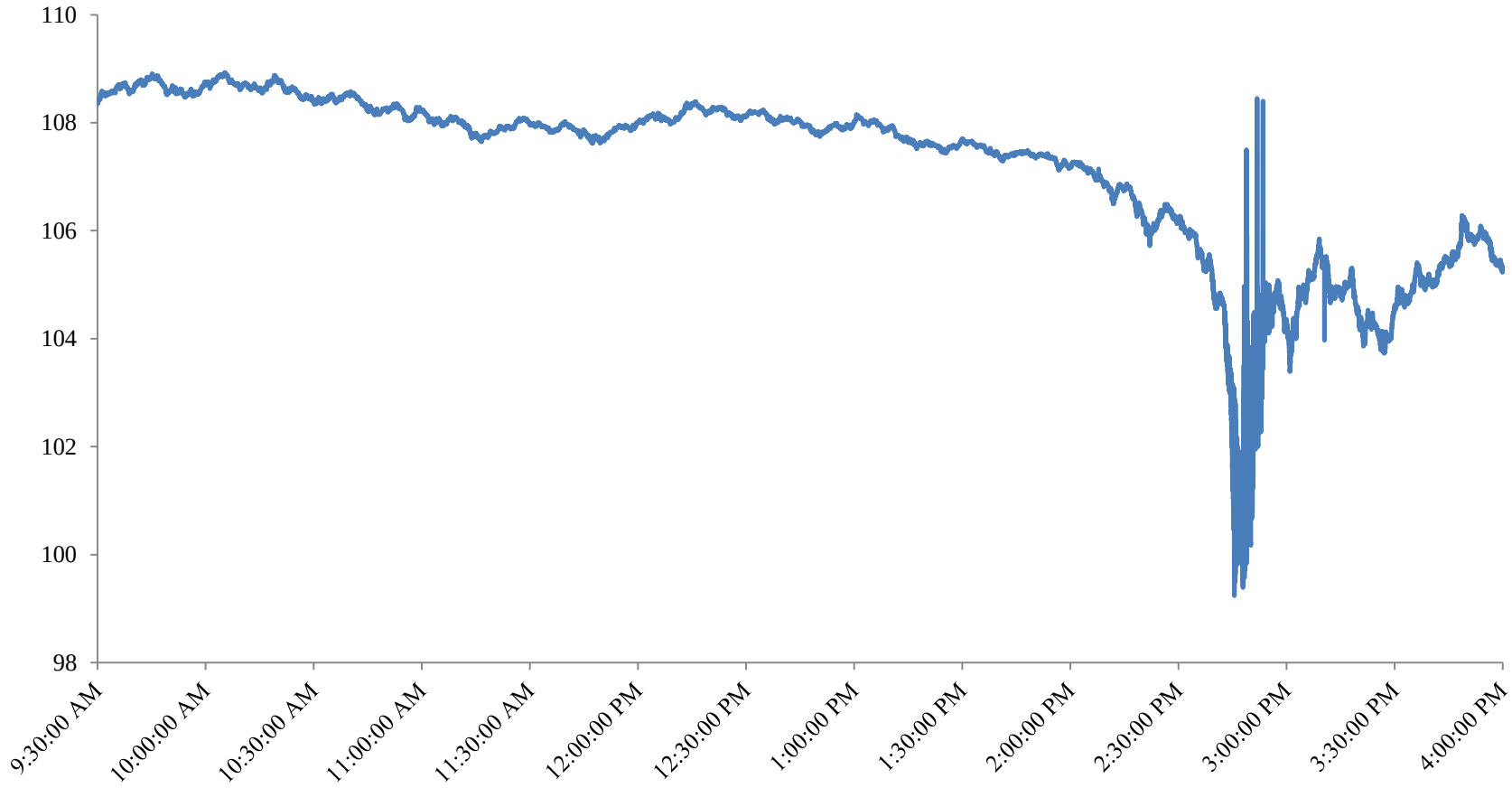

Fig. 1. Dow Jones Industrial Average ETF (May 6, 2010). This figure reports the price of the Dow Jones Industrial Average ETF on May 6, 2010. The horizontal axis shows time during the day and the vertical axis shows the level of the index.

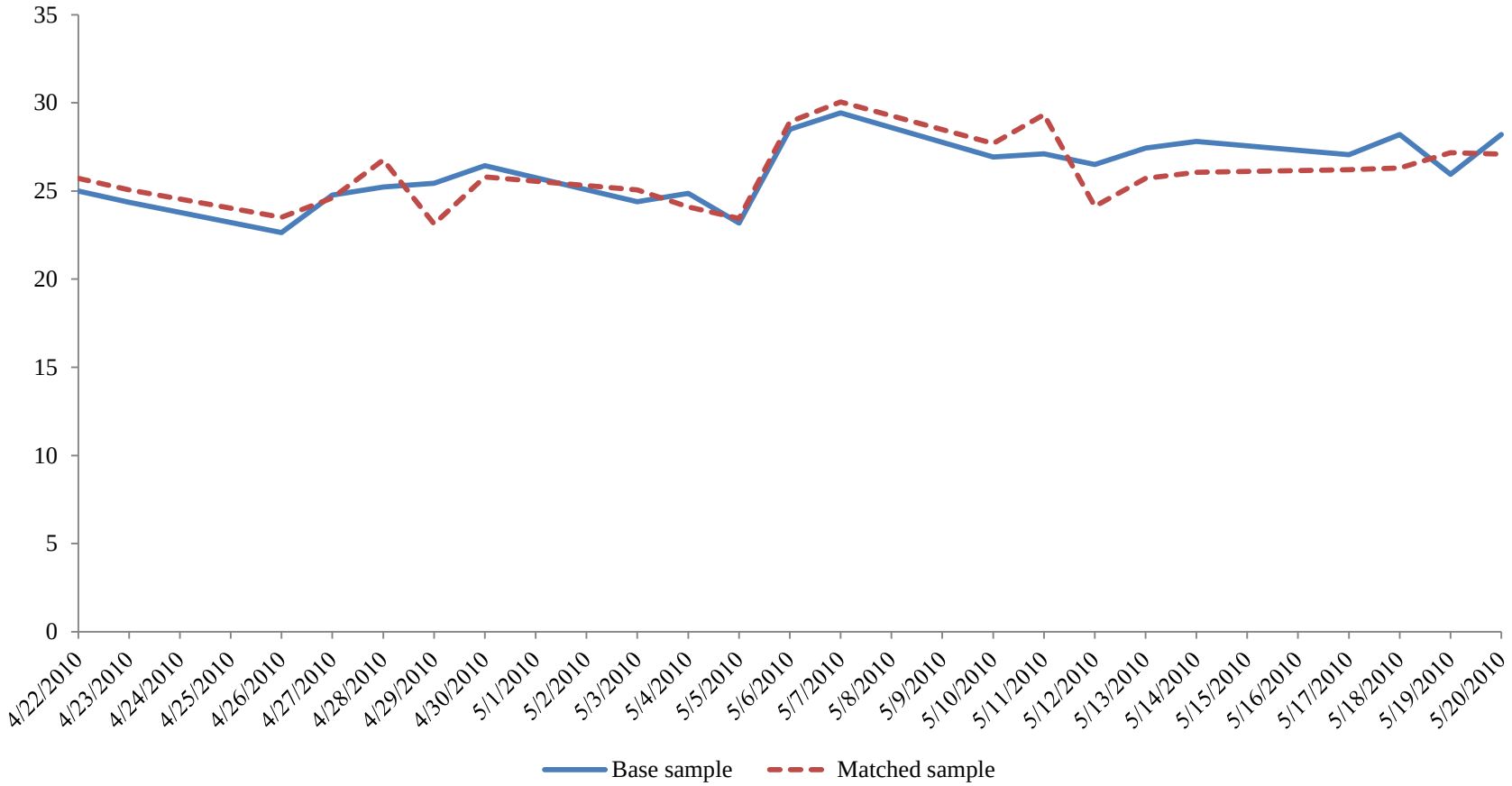

Fig. 2a. Percentage of trades executed on the New York Stock Exchange (daily). This figure reports the percentage of shares traded on NYSE to shares traded on all exchanges in the U.S. The solid line reports percentages for the base sample, which consists of the stocks of 29 NYSE-listed firms incorporated in the U.S. that had trades executed on May 6, 2010 and subsequently cancelled by either Nasdaq or NYSE Arca. Each base sample stock is matched with a stock that did not have trades cancelled on the basis of market capitalization, share price, daily turnover, and return volatility (dashed line).

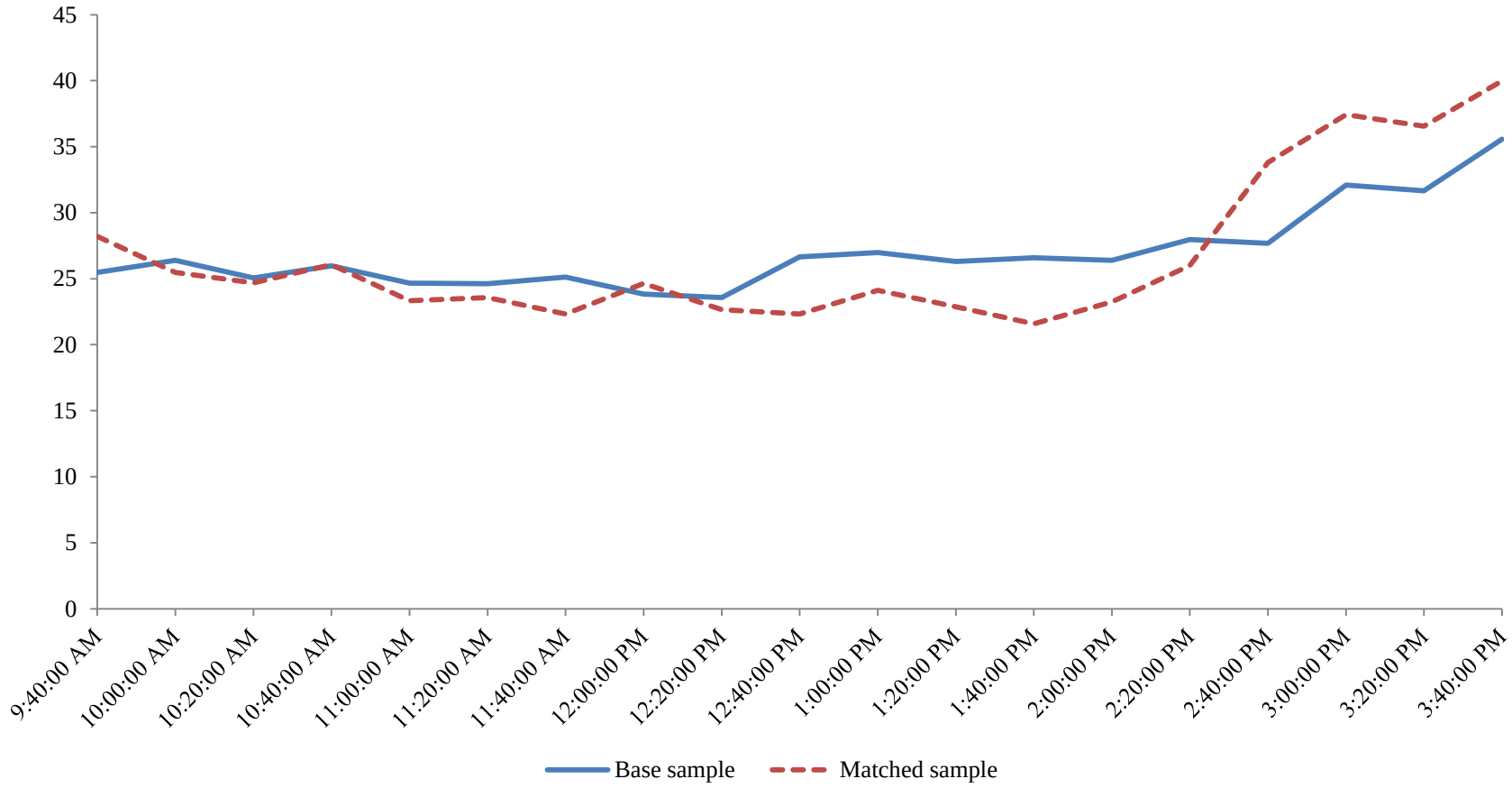

Fig. 2b. Percentage of trades executed on the New York Stock Exchange (20 minute intervals). This figure reports the percentage of trades executed on the NYSE for the base sample and the matched sample on May 6, 2010, using average values over 20 minute intervals between 9:40 a.m. and 4:00 p.m.

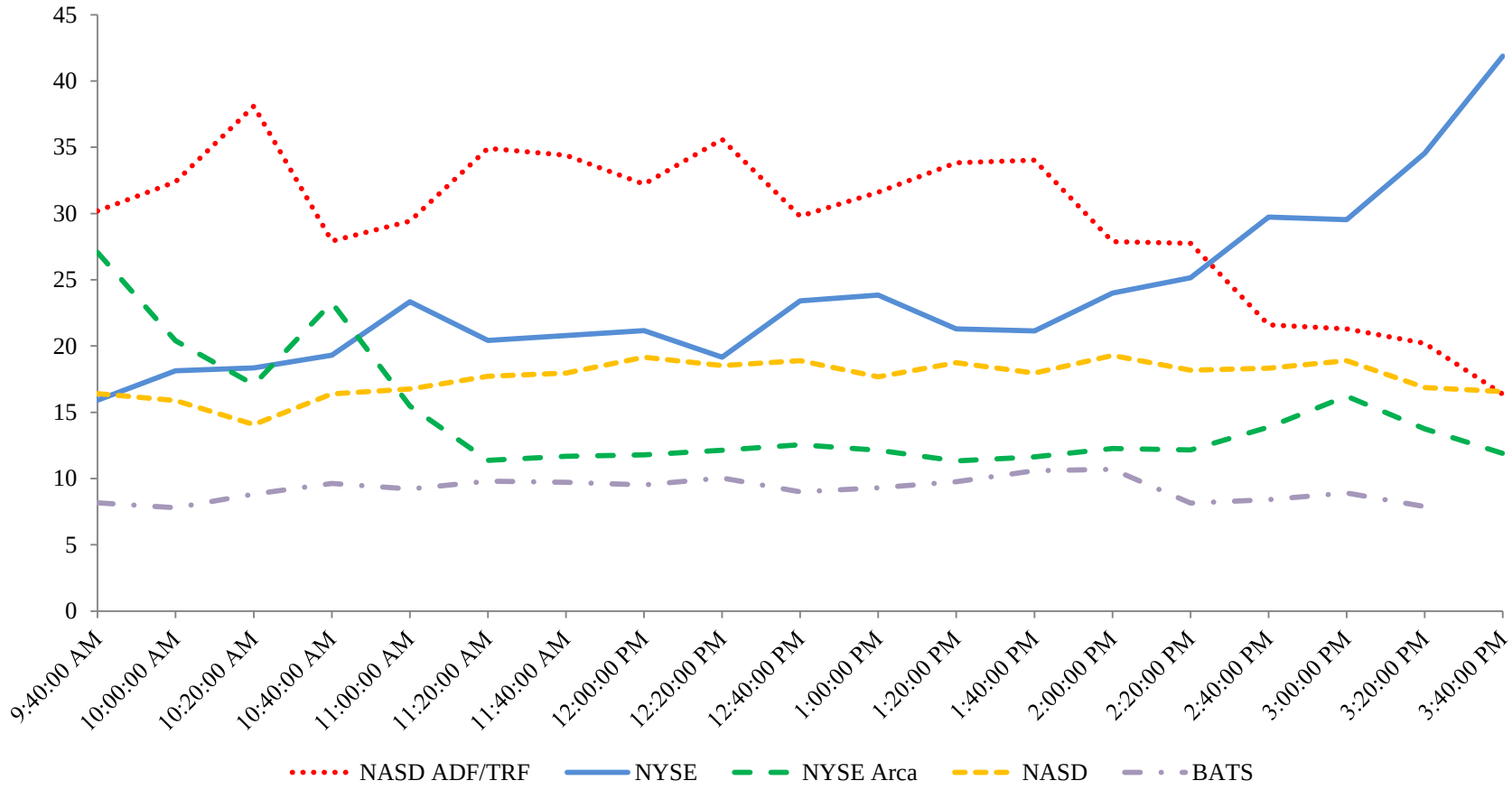

Fig. 3. Percentage of trading volume by market center (20 minute intervals). This figure reports, in 20 minute intervals, the percentage of all trades executed on the five largest market centers (by volume) between 9:40 a.m. and 4:00 p.m. on May 6, 2010.

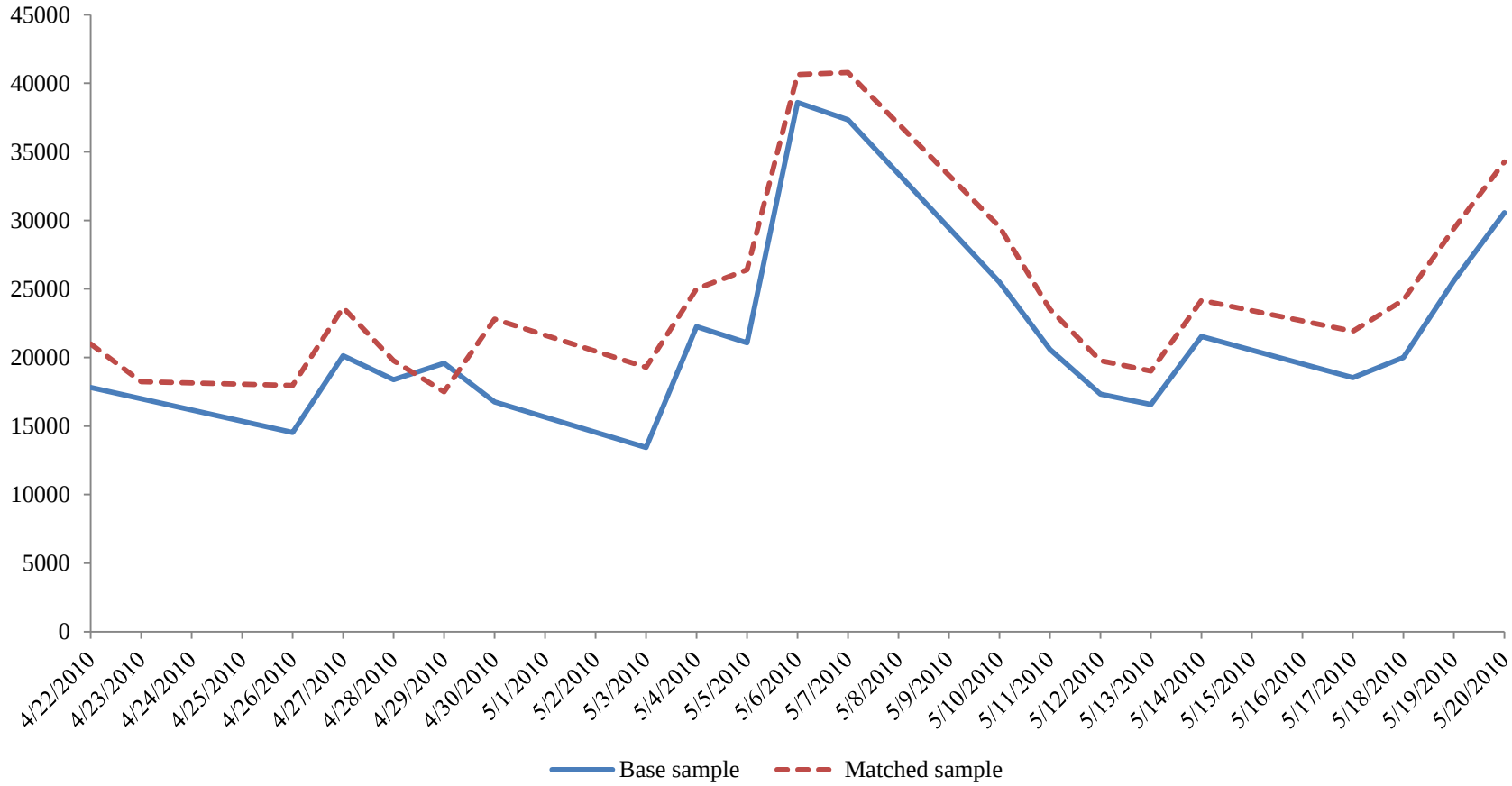

Fig. 4a. Average number of trades (daily). This figure reports the average number of trades executed at all the U.S. stock exchanges for both the base sample and the matched sample.

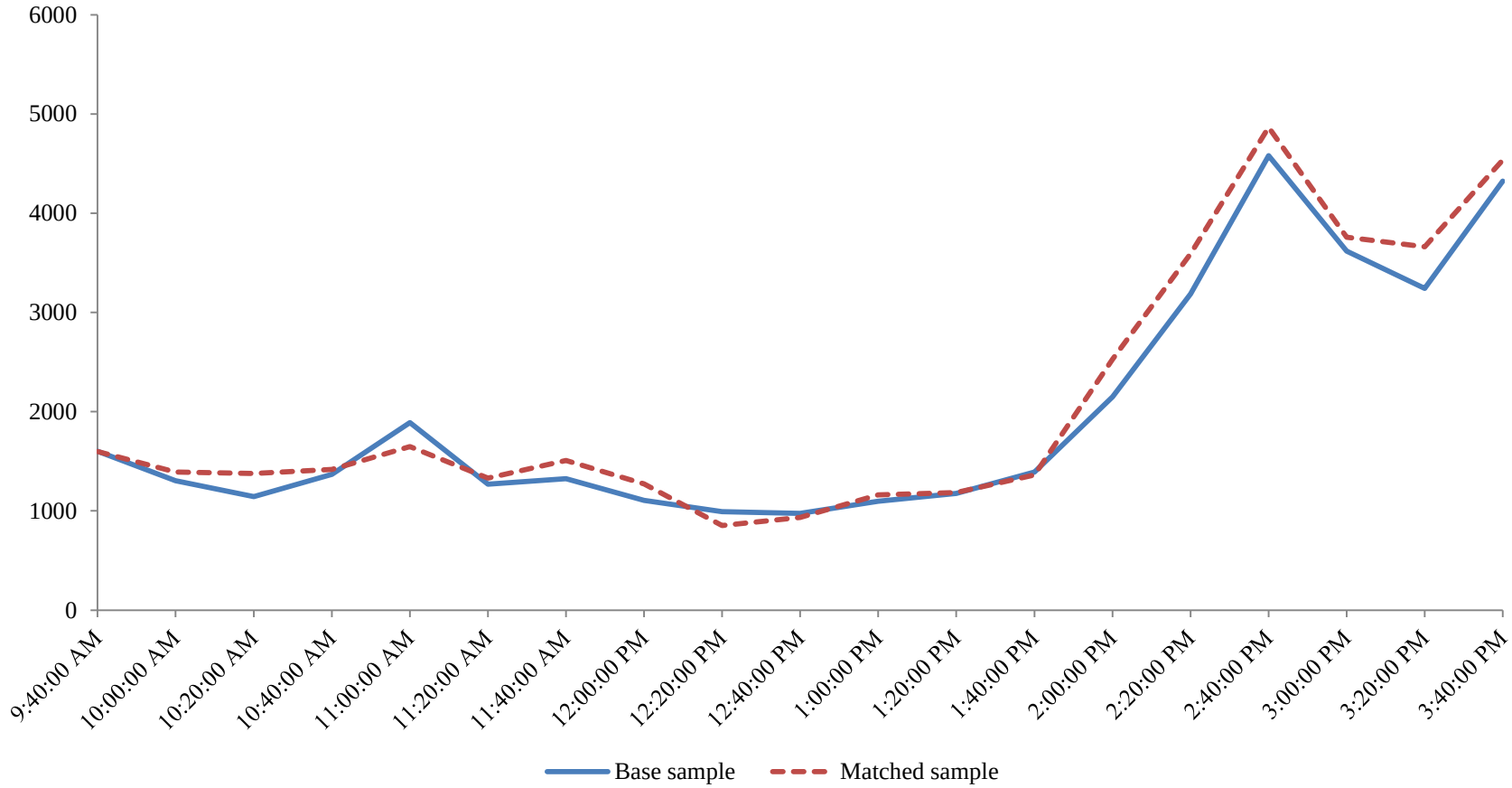

Fig. 4b. Average number of trades (20 minute intervals). This figure reports, in 20 minute intervals, the average number of trades executed for the base sample and the matched sample between 9:40 a.m. and 4:00 p.m. on May 6, 2010.

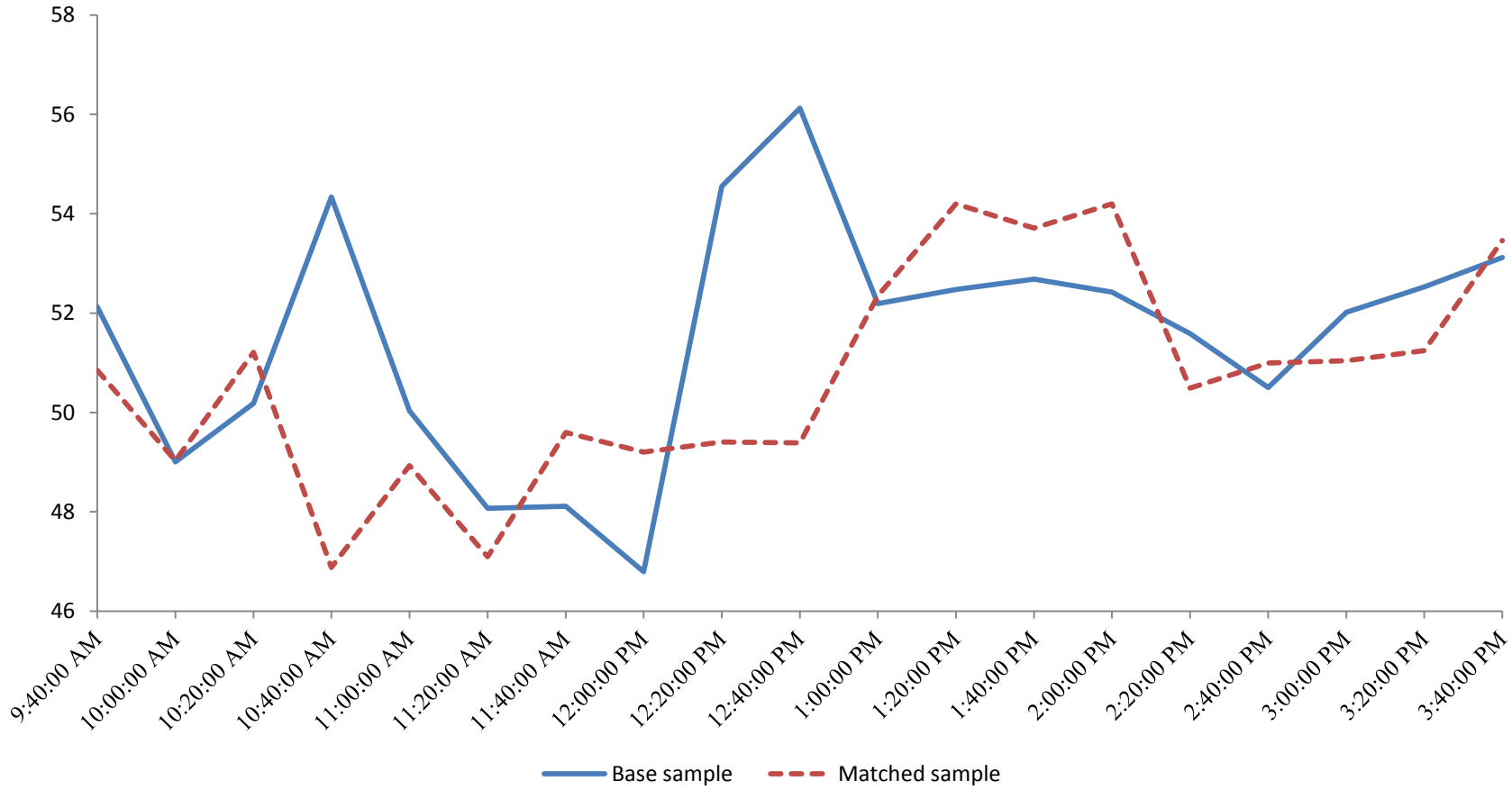

Fig. 5. Average percentage of seller-initiated trades (20 minute intervals). This figure reports, in 20 minute intervals, the percentage of all trades executed on the NYSE that are seller-initiated for both the base sample and the matched sample between 9:40 a.m. and 4:00 p.m. on May 6, 2010.

Table 1
Base sample and matched sample.

Base sample		Matched sample	
Company	Ticker	Company	Ticker
3M Co.	MMM	McDonald's Corp.	MCD
American Tower Corporation	AMT	St. Jude Medical Inc.	STJ
Arvinmeritor Inc.	ARM	Frontier Oil Corporation	FTO
B&G Foods Inc.	BGS	Comfort Systems USA Inc.	FIX
Bio-Rad Laboratories, Inc.	BIO	Kinder Morgan Management LLC	KMR
Boston Beer Co. Inc.	SAM	Ameron International Corp.	AMN
Brown & Brown Inc.	BRO	Ingram Micro Inc.	IM
CenterPoint Energy, Inc.	CNP	NiSource Inc.	NI
CenturyTel, Inc.	CTL	FirstEnergy Corp.	FE
Cenveo Inc.	CVO	The E. W. Scripps Company	SSP
Clearwater Paper Corporation	CLW	Piper Jaffray Companies	PJC
Culp Inc.	CFI	Kenneth Cole Productions Inc.	KCP
Eagle Materials Inc.	EXP	GATX Corp.	GMT
Exelon Corporation	EXC	Walgreen Co.	WAG
Health Net, Inc.	HNT	Superior Energy Services, Inc.	SPN
Hewlett-Packard Company	HPQ	The Coca-Cola Company	KO
ITC Holdings Corp.	ITC	Transatlantic Holdings Inc.	TRH
The Interpublic Group of Companies, Inc.	IPG	PulteGroup, Inc.	PHM
Iowa Telecommunications Services Inc.	IWA	Empire District Electric Co.	EDE
Lear Corp.	LEA	SPX Corporation	SPW
Merck & Co. Inc.	MRK	Wells Fargo & Company	WFC
ONEOK Inc.	OKE	Hormel Foods Corp.	HRL
Oxford Industries Inc.	OXM	Trex Co. Inc.	TREX
Philip Morris International, Inc.	PM	Abbott Laboratories	ABT
Procter & Gamble Co.	PG	Johnson & Johnson	JNJ
Quest Diagnostics Inc.	DGX	ITT Corporation	ITT
Radian Group Inc.	RDN	Avis Budget Group, Inc.	CAR
Sotheby's	BID	Tempur Pedic International Inc.	TPX
United Technologies Corp.	UTX	Occidental Petroleum Corporation	OXY

This table reports the base sample and matched sample stocks used in this study. The base sample consists of the stocks of 29 NYSE-listed firms incorporated in the U.S. that had trades executed on May 6, 2010 and subsequently cancelled by either Nasdaq or NYSE Arca. Nasdaq and NYSE Arca cancelled all trades that occurred between 2:40 p.m. and 3:00 p.m. that executed at a price that was 60 percent greater or lower than the last trade that took place at 2:40 p.m. (or immediately prior). We match each base sample stock with a matching stock that did not have trades cancelled, on the basis of market capitalization, share price, daily turnover, and return volatility. Base sample stocks that are part of the S&P 500 index as of April 1, 2010 are matched with other S&P 500 components.

Table 2
Descriptive statistics.

	Means			Medians		
	Base sample	Matched sample	Difference	Base sample	Matched sample	Difference
Market capitalization	25,571.647	27,995.022	–2423.375	3,077.971	3,483.518	–141.075**
Price	40.699	38.058	2.641	35.936	36.346	–0.567
Turnover (%)	1.059	1.058	0.001	0.692	0.827	0.009
Volatility (%)	1.772	1.789	–0.017	1.309	1.436	–0.033

This table reports descriptive statistics for the base sample and matched sample stocks and differences between the samples. Market capitalization (in millions of U.S. dollars) is the price times the number of shares outstanding on April 30, 2010. Share price is the average closing price, turnover is the average number of shares traded as a percentage of shares outstanding, and return volatility is standard deviation of daily returns calculated over the period April 1, 2010 and April 30, 2010. Significance of differences in means (medians) is assessed using paired *t*-test (Wilcoxon rank sum test).

* Statistical significance at the 10% level.
** Statistical significance at the 5% level.
*** Statistical significance at the 1% level.

Table 3
Abnormal returns.

	Base sample		Matched sample		
	Abnormal returns	% positive	Abnormal returns	% positive	Difference
April 29	0.389	48.276	0.277	55.172	0.112
April 30	0.152	62.070	1.018*	65.517	–0.866
May 3	0.253	55.172	–0.432	44.828	0.685
May 4	0.144	58.621	0.137	55.172	0.007
May 5	–0.006	51.724	–0.502	51.724	0.500
May 6	–0.796*	27.586**	–0.059	37.931	–0.736*
May 7	–0.974*	37.931	0.200	55.172	–1.133*
May 10	0.529	58.621	–0.731*	31.034*	1.260
May 11	–0.289	51.724	–0.428	37.931	0.139
May 12	–0.044	48.276	0.175	37.931	–0.219
May 13	0.296	65.510	–0.049	41.379	0.345
CAR					
[0, +5]	–1.276*	34.483	–0.930	41.379	–0.344*
[0, +3]	–1.529**	27.586**	–1.060	41.379	–0.471*
[0, +1]	–1.769***	17.241***	0.100	55.172	–1.869***

This table reports mean abnormal returns, calculated using Fama-French (1993) three-factor model augmented by Carhart's (1997) momentum factor, for the stocks in base sample and the matched sample for the 11-trading days centered on May 6, 2010. % positive represents the fraction of returns that are greater than zero. The significance of the fraction of positive returns is assessed using a sign test. Cumulative abnormal returns (CARs) are also reported for 6-, 4-, and 2-day windows beginning on May 6, 2010. Difference represents the difference in average returns between the base sample and the matched sample. Significance of the abnormal return is assessed using a *t*-test and the difference in means is assessed using a paired *t*-test.

* Statistical significance at the 10% level.

** Statistical significance at the 5% level.

*** Statistical significance at the 1% level.

Table 4
Market quality measures (daily).

Panel A: Base sample

	Date			Difference		
	5-May	6-May	7-May	Event-Pre	Post-event	Post-Pre
Absolute spread	0.040	0.041	0.056	0.001	0.015**	0.016***
Quoted spread	0.116	0.113	0.163	–0.003	0.050***	0.047***
Effective spread	0.096	0.089	0.128	–0.007	0.039***	0.032***
Quote depth	1790.900	1655.360	948.837	–135.540	–706.523***	–842.064**
Turnover (%)	0.790	1.014	1.115	0.224*	0.101	0.325***
Volume	2,458,415	2,975,994	4,212,689	517,579	1,236,695***	1,754,274**
Trades executed on NYSE (%)	22.897	25.137	30.434	2.240**	5.297***	7.537***

Panel B: Matched sample

	Date			Difference		
	5-May	6-May	7-May	Event-Pre	Post-event	Post-Pre
Absolute spread	0.034	0.028	0.041	–0.005***	0.012***	0.007**
Quoted spread	0.114	0.096	0.139	–0.018**	0.043***	0.026***
Effective spread	0.099	0.073	0.111	–0.026***	0.037***	0.011**
Quote depth	1460.700	1607.590	868.091	146.889*	–739.498***	–592.609***
Turnover (%)	0.807	0.780	1.059	–0.026	0.278***	0.252**
Volume	3,380,985	3,482,925	4,966,421	101,940	1,483,496***	1,585,436***
Trades executed on NYSE (%)	23.806	23.573	31.716	–0.233	8.143***	7.910***

Panel C: Base sample – Matched sample

	Date		
	5-May	6-May	7-May
Absolute spread	0.006	0.013**	0.015
Quoted spread	0.002	0.017*	0.023*
Effective spread	–0.003	0.016**	0.018*
Quote depth	330.201	47.769	80.746
Turnover (%)	–0.016	0.234	0.056
Volume	–922,570	–506,930	–753,732
Trades executed on NYSE (%)	–0.909	1.564	–1.282

This table reports market quality measures for the base sample and matched sample stocks on a daily basis May 5 (Pre), 6 (Event) and 7 (Post) of 2010. Panel A (B) reports this data for the stocks in the base sample (matched sample). Absolute spread represents the ask price minus the bid price for a stock. Quoted spread is the difference between bid and ask price (ask price – bid price) of a stock expressed as a percentage of the trade price. Effective spread is calculated as $2 \times S_{it} \times (P_{it} - M_{it})/M_{it} \times 100$; where S_{it} is the trade direction indicator set equal to +1 for buy orders and –1 for sell orders, constructed using a combination of the tick-test and quote-test methodology as recommended by Lee and Ready (1991) and M_{it} is the quote midpoint calculated as the ask price plus the bid price, divided by two. Quote depth represents the average depth at the prevailing National Best Bid and Offer bid and ask quotes. Turnover is the daily number of shares traded divided by the number of shares outstanding (in percent). Volume measures average trading volume across all exchanges. Trades executed on the NYSE is the average number of trades executed on the NYSE relative to the number of trades executed on all U.S exchanges (in percent). Differences between corresponding days are also reported. Panel C reports the difference in the corresponding measures between the base sample and the matched sample for each day. Significance of difference in values is assessed using paired *t*-test.

* Statistical significance at the 10% level.

** Statistical significance at the 5% level.

*** Statistical significance at the 1% level.

Table 5
Change in spreads (daily).

	Event / Pre-Event			Post-Event / Event			Post-Event / Pre-Event		
	Δ Absolute spread	Δ Quoted spread	Δ Effective spread	Δ Absolute spread	Δ Quoted spread	Δ Effective spread	Δ Absolute spread	Δ Quoted spread	Δ Effective spread
Base sample	0.003	0.006	0.006	–0.012	–0.027	–0.023	0.006	0.025	0.019
	(0.59)	(0.59)	(0.65)	(–0.81)	(–0.73)	(–0.96)	(0.59)	(1.07)	(1.31)
Δ Intraday volatility	0.001	0.012	0.038	–0.024	–0.003	0.012	–0.007	–0.003	0.017
	(0.12)	(0.35)	(1.43)	(–1.10)	(–0.05)	(0.30)	(–1.13)	(–0.13)	(0.79)
Δ Turnover	–0.005	0.002	–0.002	–0.008	–0.082*	–0.048	0.001	0.002	0.007
	(–0.88)	(0.07)	(–0.17)	(–1.14)	(–1.81)	(–1.63)	(0.25)	(0.08)	(0.57)
Δ Inverse price	–0.004	–0.055	–0.053	0.003	0.068	0.042	–0.006	0.030	0.013
	(–0.63)	(–1.48)	(–1.45)	(0.16)	(1.00)	(1.05)	(–1.05)	(0.88)	(0.63)
Base x Δ Intraday volatility	0.063*	0.087	0.054	0.038	–0.011	0.002	0.022	0.001	0.002
	(1.94)	(1.35)	(0.94)	(1.36)	(–0.14)	(0.03)	(1.44)	(0.01)	(0.07)
Base x Δ Turnover	0.006	–0.001	0.003	0.008	0.084*	0.049	–0.001	–0.012	–0.014
	(0.89)	(–0.04)	(0.18)	(1.20)	(1.84)	(1.65)	(–0.23)	(–0.59)	(–1.05)
Base x Δ Inverse price	0.004	0.018	0.036	–0.015	0.080	0.055	–0.013	0.001	0.007
	(0.35)	(0.42)	(0.80)	(–0.47)	(0.82)	(0.93)	(–1.17)	(0.02)	(0.23)
Intercept	–0.005	–0.007	–0.013**	0.024*	0.060*	0.041*	0.011**	0.018	0.001
	(–1.48)	(–0.85)	(–2.09)	(1.94)	(1.84)	(2.00)	(2.17)	(1.66)	(0.15)
Number of observations	58	58	58	58	58	58	58	58	58
R^2	0.328	0.333	0.382	0.048	0.218	0.218	0.108	0.106	0.182

This table reports OLS regressions of changes in spreads for the base sample and matched sample stocks from May 5 to May 6, 2010 (Event / Pre-Event), May 6 to May 7, 2010 (Post-Event / Event), and May 5 to May 7, 2010 (Post-Event / Pre-Event). Absolute spread represents the ask price minus the bid price for a stock. Quoted spread is the difference between bid and ask price (ask price – bid price) of a stock expressed as a percentage of the trade price. Effective spread is calculated as 2 x S_{it} x (P_{it} – M_{it})/M_{it} x 100; where S_{it} is the trade direction indicator set equal to +1 for buy orders and –1 for sell orders, constructed using a combination of the tick-test and quote-test methodology as recommended by Lee and Ready (1991) and M_{it} is the quote midpoint calculated as the ask price plus the bid price, divided by two. Base sample is an indicator set equal to 1 for stocks that had trades that executed on May 6, 2010 that were subsequently cancelled by the Nasdaq or NYSE Arca and zero for matched sample stocks. Intraday volatility is the standard deviation of open-to-close mid-quote returns, measured over 20-minute intervals. Turnover is the ratio of shares traded to shares outstanding. Inverse price is the ratio of 1 to the stock price. Robust *t*-statistics are reported in parentheses.

* Statistical significance at the 10% level.
** Statistical significance at the 5% level.
*** Statistical significance at the 1% level.

Table 6
Market quality measures (two-week intervals).

Panel A: Base sample

	Mean			Median		
	May 7 – May 20	April 22 – May 5	Difference	May 7 – May 20	April 22 – May 5	Difference
Absolute spread	0.039	0.034	0.005**	0.019	0.015	0.002***
Quoted spread	0.111	0.093	0.018***	0.073	0.063	0.012***
Effective spread	0.086	0.072	0.014***	0.069	0.054	0.008***
Quote depth	2585.300	3314.150	–728.850***	926.327	1570.380	–399.245***
Turnover (%)	1.541	1.226	0.315*	0.917	0.762	0.156**
Volume	4,466,742	3,846,983	619,759	1,812,562	1,632,800	57,741**
Trades executed on NYSE (%)	27.462	24.631	2.831***	27.647	25.574	1.207***

Panel B: Matched sample

	Mean			Median		
	May 7 – May 20	April 22 – May 5	Difference	May 7 – May 20	April 22 – May 5	Difference
Absolute spread	0.029	0.026	0.003**	0.019	0.017	0.001***
Quoted spread	0.098	0.086	0.012***	0.068	0.060	0.006***
Effective spread	0.075	0.067	0.009***	0.055	0.051	0.005***
Quote depth	2205.890	2935.280	–729.390***	709.969	942.272	–214.681***
Turnover (%)	1.192	1.242	–0.050	0.910	0.854	0.107
Volume	5,168,037	4,489,347	678,689	1,912,411	1,782,376	54,663
Trades executed on NYSE (%)	26.978	24.719	2.258***	27.474	26.441	2.185***

Panel C: Base sample – Matched sample

	Mean		Median	
	May 7 – May 20	April 22 – May 5	May 7 – May 20	April 22 – May 5
Absolute spread	0.010**	0.008	0.001	0.000
Quoted spread	0.013	0.007	0.004*	0.000
Effective spread	0.010	0.005	0.005**	0.002
Quote depth	379.410	378.870	32.442	–36.947
Turnover (%)	0.348	–0.016	–0.022	–0.015
Volume	–701,294	–642,364	–20,136	–87,954*
Trades executed on NYSE (%)	0.485	–0.089	–0.536	1.273

This table reports the mean and median daily average market quality measures over two week intervals (a) preceding the flash crash (April 22 – May 5) and (b) following the flash crash (May 7 – May 20). Absolute spread represents the ask price minus the bid price for a stock. Quoted spread is the difference between bid and ask price (ask price – bid price) of a stock expressed as a percentage of the trade price. Effective spread is calculated as $2 \times S_{it} \times (P_{it} - M_{it})/M_{it} \times 100$; where S_{it} is the trade direction indicator set equal to +1 for buy orders and –1 for sell orders, constructed using a combination of the tick-test and quote-test methodology as recommended by Lee and Ready (1991) and M_{it} is the quote midpoint calculated as the ask price plus the bid price, divided by two. Quote depth represents the average depth at the prevailing National Best Bid and Offer bid and ask quotes. Turnover is the daily number of shares traded divided by the number of shares outstanding (in percent). Volume measures average trading volume across all exchanges. Trades executed on the NYSE is the average number of trades executed on the NYSE relative to the number of trades executed on all U.S exchanges (in percent). Difference represents the mean difference over the May 7 – May 20 period and the April 22 – May 5 period. The median difference is also reported. Panel A (B) reports the results for the base sample (matched sample). Panel C shows the mean and the median difference between the base sample and the matched sample over the corresponding time periods. Significance of difference in values of means (medians) is assessed using paired *t*-test (Wilcoxon rank sum test).

* Statistical significance at the 10% level.

** Statistical significance at the 5% level.

*** Statistical significance at the 1% level.

Table 7
Change in spreads (two-week intervals).

	Δ Absolute spread	Δ Quoted spread	Δ Effective spread
Base sample	0.004	0.005	0.004
	(1.41)	(0.64)	(0.73)
Δ Intraday volatility	0.039	0.090*	0.054*
	(1.55)	(1.91)	(1.93)
Δ Turnover	–0.004*	–0.004	0.001
	(–1.91)	(–0.69)	(0.39)
Δ Inverse price	–0.008**	–0.000	0.005
	(–2.21)	(–0.03)	(0.90)
Base x Δ Intraday volatility	–0.034	–0.019	–0.008
	(–1.09)	(–0.27)	(–0.17)
Base x Δ Turnover	0.005	0.001	–0.002
	(1.40)	(0.15)	(–0.29)
Base x Δ Inverse price	0.004	0.002	–0.001
	(0.82)	(0.14)	(–0.06)
Intercept	0.002*	0.004	0.002*
	(1.72)	(1.55)	(1.98)
Number of observations	58	58	58
R^2	0.104	0.142	0.229

This table reports OLS regressions of changes in spreads for the base sample and matched sample from the two weeks preceding the flash crash (April 22 – May 5) through two weeks following the flash crash (May 7 – May 20). Absolute spread represents the ask price minus the bid price for a stock. Quoted spread is the difference between bid and ask price (ask price – bid price) of a stock expressed as a percentage of the trade price. Effective spread is calculated as $2 \times S_{it} \times (P_{it} - M_{it})/M_{it} \times 100$; where S_{it} is the trade direction indicator set equal to +1 for buy orders and –1 for sell orders, constructed using a combination of the tick-test and quote-test methodology as recommended by Lee and Ready (1991) and M_{it} is the quote midpoint calculated as the ask price plus the bid price, divided by two. Base sample is an indicator set equal to 1 for stocks that had trades that executed on May 6, 2010 that were subsequently cancelled by the Nasdaq or NYSE Arca and zero for matched sample stocks. Intraday volatility is the standard deviation of open-to-close mid-quote returns, measured over 20-minute intervals. Turnover is the ratio of shares traded to shares outstanding. Inverse price is the ratio of 1 to the stock price. Robust *t*-statistics are reported in parentheses.

* Statistical significance at the 10% level.
** Statistical significance at the 5% level.
*** Statistical significance at the 1% level.

Table 8
Options markets.

	Base sample				Matched sample			
	Implied Volatility	Delta	Gamma	Vega	Implied Volatility	Delta	Gamma	Vega
April 29	0.311	0.528	0.193	8.483	0.314	0.532	0.174	7.304
April 30	0.353	0.527	0.159	9.176	0.331	0.531	0.164	7.809
May 3	0.322	0.527	0.184	8.862	0.308	0.533	0.182	7.515
May 4	0.347	0.526	0.174	9.250	0.343	0.531	0.164	8.085
May 5	0.360	0.527	0.171	9.460	0.360	0.529	0.152	8.327
May 6	0.462	0.528	0.120	10.766	0.415	0.530	0.137	9.247
May 7	0.458	0.529	0.131	10.563	0.449	0.531	0.128	9.936
May 10	0.368	0.527	0.156	9.429	0.376	0.528	0.148	8.592
May 11	0.381	0.527	0.164	9.640	0.380	0.529	0.145	8.749
May 12	0.355	0.529	0.156	9.087	0.338	0.532	0.165	8.118
May 13	0.362	0.528	0.158	9.370	0.359	0.534	0.161	8.572
Difference								
[–1,0]	0.102***	0.001	–0.051*	1.306***	0.056***	0.001	–0.015***	0.920***
[–1,1]	0.098**	0.002	–0.040**	1.103***	0.090***	0.002	–0.023***	1.609***
[–3,3]	0.059***	0.000	–0.020*	0.778***	0.072***	–0.003	–0.038***	1.234***
Base – Matched								
[–1,0]	0.046	0.000	–0.036	0.386				
[–1,1]	0.008	–0.001	–0.017	–0.506				
[–3,3]	–0.013	0.004	0.018	–0.456				

This table reports the option related measures for the base and matched sample stocks with tradable options. All calculations use historical LIBOR/Eurodollar rates for interest rate inputs, and correctly incorporate discrete dividend payments. Variables are calculated using at-the-money forward call options with 30 days to expiration. We report the implied volatility, delta, gamma and vega on a daily basis for the 11-trading days centered on May 6, 2010. Difference denotes the change in the measure in a trading window. For example, [–1,0] represents the change from day –1 to day 0. Base–Matched denotes the difference in the respective measure between the base sample and the matched sample. Significance of the difference is assessed using a *t*-test. Significance of Base-Matched is assessed using a paired *t*-test.

* Statistical significance at the 10% level.
** Statistical significance at the 5% level.
*** Statistical significance at the 1% level.