Quote Stuffing and Market Quality

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Abstract

Quote stuffing is the practice of placing a large number of orders and cancelling them quickly. We identify numerous events of this kind in the period from 2008-2016 since Reg. NMS has been in place, with a peak average of 917 episodes per day in 273 symbols in 2011. We find that quote stuffing is harmful to market quality, widening spreads and raising volatility. This occurs not only on the Nasdaq where we observe the quote stuffing, but also on the NYSE, Archipelago and Amex. Trading rises though, and the market share of high frequency trading increases as well during these episodes. We estimate that each $1,000$ cancellations during the quote stuffing are associated with 420 shares of high frequency trading volume on average. Trading activity migrates off exchange, with the median TRF volume that doubles during quote stuffing events. Both aggregate message traffic and quote stuffing slow down the Securities Information Processor.

`Keywords`: high frequency trading; quote stuffing; market quality; externality; SIP delays

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1. Introduction

On January 13, 2017, the U.S. Securities and Exchange Commission fined Citadel Securities $22.6 million dollars[1] for the use of two algorithms that "...did not internalize retail orders at the best price observed nor sought to obtain the best price in the marketplace." Citadel's high frequency trading strategy exploited differences between prices on the Securities Information Processor (SIP) and the more accurate direct exchange feeds. Citadel handles approximately 35% of the U.S. retail equity order flow, and this makes understanding the effects of message intensive activity essential.

High frequency trading (HFT) represents the majority of equity market trading volume since the final passage of Reg. NMS in August 2007. There is an active academic debate as to whether HFT is harmful to market quality.

Some papers suggest that HFT improves market quality. Hasbrouck and Saar (2013) analyze the ITCH data feed from Nasdaq. They identify HFT activity by orders linked closely in time. From these matched orders, they suggest that HFT activity lowers short-term volatility and bid-ask spreads, and increases displayed depth. Brogaard, Hendershott and Riordan (BHR, 2014) analyze a data set from Nasdaq that identifies HFT firms. They find that HFT increases price efficiency through their marketable orders. Carrion (2013) studies the same data set as BHR and concludes that HFT participants supply liquidity when it is low and take liquidity when it is high. Menkveld (2013) analyzes the arrival of the Chi-X high frequency platform in Europe, the most active European trading network, and concludes that HFT traders act as market makers in the new market. Brogaard, Hagströmer, Norden and Riordan (2014) find that fast and colocated traders improve market liquidity at Nasdaq OMX Stockholm by relaxing their inventory management constraints.

On the contrary, other papers find pernicious effects of HFT on market quality. Gai, Yao and Ye (2014) find that exogenous latency reduction at Nasdaq that lead to more HFT activities do not improve market liquidity but generate externatilities. Menkveld and Zoican (2014) have a similar finding that adverse selection cost and effective spread rise after an improvement in speed at Nasdaq OMX Nordic. Three studies have re-examined the BHR data set and reached different conclusions. Brogaard, Hendershott and Riordan (2013) use the 2008 short sale ban as an exogenous shock and find that HFT traders decrease liquidity and increase volatility. Gao and Mizrach (2016) find that HFT traders decrease their market making activity and increase their aggressive trades during

[1] See https://www.sec.gov/news/pressrelease /2017-11.html

Federal Reserve Treasury purchases. Hirschey (2013) notes that HFT firms anticipate the order flow from non-HFT investors and their aggressive trades are highly correlated with future returns. Breckenfelder (2013) studies the competition among HFT traders at Nasdaq OMX Stockholm and finds that it leads to a decline in liquidity and a rise in short-term volatility.

Judging HFT as solely “good” or “bad” is too general given the fact that it covers a variety of strategies that may impact the market differently. Hagströmer and Norden (2013) divide HFT into market making and opportunistic specializations, and find that the majority of HFT volume comes from market making activities. Biais and Foucault (2014) discuss the HFT heterogeneity and classify HFT strategies in five categories ranging from market making to manipulation. On one hand, high frequency market makers are generally deemed as beneficial to the market, as shown theoretically by Jovanovic and Menkveld (2012) and empirically by Menkveld (2013) and others. On the other hand, Menkveld and Zoican (2014) find that market quality deteriorates when high frequency speculators are also taken into account. The diversity of HFT strategies suggests that analyzing the average effect of HFT may provide a misleading conclusion on its impact on market quality.

Although HFT market making constitutes a large share of HFT activities, HFT strategies are more profitable from aggressive trading. Baron, Brogaard and Kirilenko (2012) analyze data from the Commodity Futures Trading Commission that identifies the HFT participants. They study the profitability of HFT in the E-mini futures contract and find that aggressive HFT strategies make higher profits than mixed or passive HFT strategies. BHR (2014) find that HFT traders earn high profits in liquidity demanding trades and suffer losses in liquidity supplying trades without fee rebates. Baron, Brogaard, Hagströmer and Kirilenko (2016) analyze the Swedish HFT industry. They note that the fastest firms earn disproportionate profits.

HFT enables the fastest traders to gain the largest profits as they can process news quickly. Several studies provide theoretical models in which HFT firms have speed advantage upon news arrivals. Biais, Foucault and Moinas (2014) and Hoffmann (2014) suggest that differences in speed increase adverse selection costs and thus HFT generates negative externalities and reduces social welfare. Foucault, Hombert, and Roşu (2013) argue that the ability of HFT firms to receive news faster creates additional information asymmetry and thus reduce liquidity. Martinez and Roşu (2013) model HFT participants as informed traders who observe news stream and trade quickly. They find that HFT generates trading volume and volatility and decreases liquidity.

HFT participation has also dramatically increased the number of orders entering the equity market. We document a rise in the cancellation to execution ratio in ITCH from 28 in 2008 to 84 in 2013. Apart from this rising trend, stocks frequently exhibit bursts in quoting and cancellation activity that do not appear to be related to fundamentals. In this paper we analyze these "quote stuffing" episodes that often occurred in the absence of news.

Quote stuffing has been documented in ITCH data by Gai, Yao and Ye (2014) at the level of individual Nasdaq servers. They find the evidence that message flows of stocks on the same server tend to move together. Hasbrouck (2015) also suggests that high frequency oscillations in quoting contribute to the short-term volatility after Reg. NMS. Eggington, Van Ness and Van Ness (2013) analyze these episodes across exchanges and find hundreds of cases per day. The theoretical model by Baruch and Glosten (2013) suggests that fleeting orders are an outcome of a benign equilibrium where strategic liquidity suppliers manage their risk. While it provides a possible explanation for fleeting quotes, their model is based on the assumption that the short lived orders are used solely by liquidity providers. However, HFT aggressive strategies may create fake news events by submitting and quickly cancelling a large amount of quotes as a way to make profits.

We identify numerous episodes of high frequency cancellations since Reg. NMS has been implemented. The number of occurrence peaks in 2011 with an average of 917 episodes per day in 273 symbols. Cartea, Payne, Penalva, and Tapia (2015) examine similar bursts of quote activity which are associated with wider spreads and lower depth. We also find that quote stuffing has detrimental impact on market quality. Volatility increases and bid-ask spreads widen persistently following quote stuffing. We observe the effects not only on Nasdaq where quote stuffing occurs, but also on NYSE, Arca, and Amex.

An important issue on quote stuffing is whether it generates negative externalities to other market participants. However, we find that trading activity of the same stock rises on Nasdaq and other exchanges during quote stuffing events. We observe that the share of HFT aggressive volume increases during these episodes. We estimate that on average each $1,000$ cancellations are associated with 420 shares of HFT volume in the quote stuffing minute from 2008-2016. The connection between cancellations and HFT aggressive activities is the strongest in 2013, with $6,660$ HFT shares for each $1,000$ cancellations. Another externality from high frequency cancellations is that trading activities appear to go off exchange when quote stuffing is happening.

We also examine a potential market wide externality. Gai, Yao and Ye (2014) argue that the message flow of a stock could block trading of stocks on the same Nasdaq server. We observe a similar mechanism operating through the Securities Information Processor (SIP), the inter-market price server that establishes the protected quotes in the national best bid and offer (NBBO). Aggregate ITCH activity slows the SIP. Between 2015 and 2016, an increase of $80,210$ ITCH messages slows the SIP by one millisecond. Quote stuffing has an important marginal effect on the symbol impacted. Only 268 HFT cancellation messages provides the same one millisecond increase in latency.

The paper is organized as follows. Section 2 describes the ITCH data set at the message level and presents our definition of HFT activity. Section 3 describes annual trends in quote stuffing events. Section 4 describes the effects on market quality on Nasdaq where our quote stuffing events originate. Section 5 reports the same market quality metrics for other exchanges. Section 6 looks at trading activity which rises on both Nasdaq and other exchanges. On Nasdaq, we document that HFT aggressive strategies grab a larger market share of the higher trading activity. Dark pools also grab a larger market share. Section 7 looks at quote stuffing externalities. In Section 8 we analyze its impact on the SIP. Section 9 concludes.

2. ITCH

Identifying the effects of high frequency trading requires data at the messaging level. ITCH is the underlying message feed for the Nasdaq Totalview, the most comprehensive order book that Nasdaq provides to market participants. We list the messages, in Table 1, analyzed in this manuscript, all of which change the status of the order book in some way.

[INSERT Table 1 HERE: Description of ITCH Messages]

Market makers can enter multiple quotes at different price tiers in the book, and they can also choose to display their market participant ID (MPID) or to trade anonymously. An F message indicates an addition to the order book with the MPID, and an A message is anonymous. Each message enters with an order number. The link between the orders enables us to determine the time between when an order enters and leaves the book.

Messages can leave in five ways. We can see an execution against that quote with the message E. This determines the aggressive side in the trade, so there is no ambiguity about trade direction. Trades occasionally execute at a different price than quoted, and these trades are designated with the message symbol C. Orders can be deleted in their entirety, and these messages are designated with a D. An order can be partially deleted, which is a X message. Orders can also be cancelled and replaced, and these are designated with an U.

Time stamps are in nanoseconds. We define a high frequency message as any order chain with 50 millisecond link or less. This is the same definition used in Hasbrouck and Saar (2012), Hasbrouck (2013), and Ye, Yao and Gai (2013). Only HFT firms are able to operate with this latency which requires extensive infrastructure investments.

Our analysis proceeds with a definition of quote stuffing events. We then turn to the effects on market quality of quote stuffing.

3. Quote Stuffing Trends

We have ITCH data going back to August 2003, but we analyze the data following Reg. NMS, from 2008-2016.

3.1 Definition

We analyze the data in one-minute intervals. This appears to be long enough to capture quote stuffing in both large and small capitalization stocks. We analyze the 380 minutes from 09:35 to 15:55. This helps us to avoid problems at the open and close which may distort our measures.

We take the intersection of stocks listed in ITCH with those in Compustat. There are approximately $7,000$ ticker symbols that we analyze on a given trading day.

For C, D, E, U and X messages, we count the number of occurrences of both HFT and non-HFT messages, $\#M^{HFT}, \#M^{nHFT}$, etc.

We define our quote stuffing events using three criteria. We first identify a 30-standard deviation increase in HFT cancellation frequency compared to the moving average of the preceding 22 days during that minute

$$zM_{i,t,n}^{HFT} = \frac{\#M_{i,t,n}^{HFT} - \overline{M}_{i,t,n-1}^{HFT}}{\sigma(M_{i,t,n-1}^{HFT})} \tag{1}$$

where

$$\overline{M}_{i,t,n-1}^{HFT} = \textstyle\sum_{j=1}^{22} \#M_{i,t,n-j}^{HFT}/22$$

and

$$\sigma(M_{i,t,n-1}^{HFT}) = \sqrt{\textstyle\sum_{j=1}^{22} (\#M_{i,t,n-j}^{HFT} - \overline{M}_{i,t,n-1}^{HFT})^2/21}$$

This is our measure of volatility. To avoid very illiquid stocks, we also require at least 500 HFT cancellations in the minute, $\#DUX_{i,t,n}^{HFT} \geq 500$.

Finally, since news is likely to generate additional quoting activity, we filter out any stocks that have Reuters news stories on the day before, the day of, and the day after the quote stuffing occurs.

3.2 Frequency of events

Even at the 30 standard deviation threshold, there are a surprisingly large number of quote stuffing events. An event is an occurrence in any symbol at the one-minute time frame on one side of the book. If quote stuffing occurs on both the bid side and the ask, this counts as two events in our sample.

[INSERT Figure 1 HERE: Average Daily Quote Stuffing Events 2008-15]

Quote stuffing becomes more frequent in the first five years of our sample. There are an average of 673 episodes per day in 2008, 783 in 2009, 911 in 2010, 917 in 2011, and 664 in 2012.

The number of events has been falling since 2012 though, and the frequency in 2013-2016 is only 30% of the 2008 level. This is consistent with industry reports[2] that the share of high frequency trading volume has been falling recently. Quote stuffing appears to have stabilized at this lower plateau during the last three years.

3.3 Characteristics

We next graph the average number of different listings that are impacted each day. These follow a similar trend to the number of events

[INSERT Figure 2 HERE: Average Daily Symbols Impacted by Quote Stuffing 2008-16]

162 stocks per day are impacted in 2008. The number of effected symbols rises steadily, peaking at 273 in 2011. There is a slowdown in 2012, followed by a substantial decline to an average of only 85 symbols per day in 2013-2016.

We report summary statistics on the symbols impacted by quote stuffing in Table 2. The data are drawn from CRSP and represent the volume and market capitalization at the start of the trading month.

[2] See the estimates by the Tabb Group and Rosenthal Securities, http://www.nytimes.com/ interactive/2012/10/15/ business/Declining-US-High-Frequency -Trading.html?_r=1&. Profits also appear to have fallen as well.

[INSERT Table 2 HERE: Stock Characteristics]

The average market capitalization of the effected symbols is the largest in 2014 at over $4.3 billion. The size of the stocks appears relatively stable with market cap averages rising and falling with the market as a whole.

The average volume is highest in 2016 at just over 2.1 million shares. Volume in the quote stuffing symbols rises in 2012-2014 even though market volumes were down in those years.

The ten largest stocks are also impacted, but these episodes appear to be news related. AAPL, for example, has an average of more than 100 quote burst episodes from 2008 to 2012, but all of these are removed by our news filter. After news filtering, only Berkshire Hatheway remains in our news filtered sample. It has events in each year from 2009 to 2013, with 124 events in 2010.

Since our message traffic is from Nasdaq's ITCH feed, it is perhaps not surprising that more than 40% of the events are in Nasdaq listed stocks. This percentage peaks in 2016, when it exceeds 54%. The NYSE has fallen from nearly 42% to 30%. There is a rise in Archipelago listings from 30% in 2008 to 35% in 2015, but this appears to be ETF related.

About 50% of our events are in common shares, 30% in ETFs, and 20% in other types (non-U.S. listings, preferred shares, REITs, etc.). ETFs make up 30% of events in 2008, rising to 39% in 2015. All of this comes from a decline in events in common stock listings, which drop from 49% in 2008 to 40% in 2015.

4. Market Quality on Nasdaq

Because the quote stuffing we document is occurring on Nasdaq, we first examine market quality metrics on Nasdaq itself.

We first look at volatility, measured as the high-low range in a one-minute interval on the bid side[3] of the order book, $HL_{i,t+1,n}$,

$$HL_{i,t,n} = \frac{p_{i,t,n}^{high} - p_{i,t,n}^{low}}{0.5 \times (p_{i,t,n}^{high} + p_{i,t,n}^{low})}. \tag{2}$$

We compare the volatility for stocks experiencing quote stuffing in the minute after the burst ensues to the volatility of the same security in the same minute on the prior day. Given the heterogeneity of stocks in the quote stuffing sample, a large frequency of extreme observations result in a non-normal distribution of volatility difference. Therefore, it is inappropriate to test

[3] The results for ask-side volatility are qualitatively similar to the bid side.

the mean difference. Instead, we conduct a non-parametric Wilcoxon signed rank test

$$W = |\Sigma_i \left[sign(HL_{i,t+1,n} - HL_{i,t+1,n-1}) \cdot R_i \right]| \,, \tag{3}$$

where R_i is the rank of the absolute difference $|HL_{i,t+1,n} - HL_{i,t+1,n-1}|$ for stock i, and $sign(x)$ equals 1 if $x > 0$, 0 if $x = 0$, and -1 if $x < 0$. The test has greater efficiency than paired t-test on non-normal distributions. The null hypothesis is that the median difference between volatility on day n at time $t+1$ and that at the same minute on the prior day $n-1$ is zero. We use the one-sided test and the alternative is that volatility rises during quote stuffing. In Table 3, we show that this is overwhelmingly the case.

[INSERT Table 3 HERE: Bid Volatility]

We reject for all years, 2008-2016, that volatility is constant. Volatility more than doubles from 43.0 to 111.4 basis points (bps) at the 90th percentile during the minute after a quote stuffing event.

The next measure is the bid-ask spread. We use the inside spread from the NYSE Trade and Quote Database (TAQ) and report the average bid-ask spread within a one-minute interval in Table 4.

[INSERT Table 4 HERE: Percentage Bid-Ask Spread]

The quoted spread is measured in percent in the minute after the quote burst,

$$S_{i,t+1,n} = \frac{p^a_{i,t+1,n} - p^b_{i,t+1,n}}{0.5 \times (p^a_{i,t+1,n} + p^b_{i,t+1,n})}. \tag{4}$$

The median inside spread on Nasdaq rises by 3.4 bps, from 20.0 to 23.4 bps. Looking at the 90th percentile, the rise in spreads is even more dramatic, a 33 bps increase from 121.4 to 154.6 bps. The Wilcoxon signed rank test rejects at the 33 standard deviation level or greater in each year of the sample.

Our final two measures of market quality relate to the number of messages required to execute a trade. The first measure, which we have just for Nasdaq, is the cancellation to execution ratio. Using the message symbols from Section 2, we define the HFT cancellation to execution ratio as

$$CR^{HFT}_{i,t,n} = \frac{\#D^{HFT}_{i,t,n} + \#U^{HFT}_{i.t,n} + \#X^{HFT}_{i.t,n}}{\#C^{HFT}_{i,t,n} + \#E^{HFT}_{i,t,n}}. \tag{5}$$

We narrow the cancellation ratio to restrict it to high frequency activity using the 50 millisecond rule. We contrast the HFT cancellation ratio for a symbol with its cancellation ratio on the previous day at the same minute. We then test formally for differences in the median using the Wilcoxon signed rank test. To better visualize the changes, we graph the 90th percentile of the distributions in Figure 3.

[INSERT Figure 3 HERE: Cancellation to Execution Ratio]

In the upper tails of the distribution, we can easily see the effect of the bursts. They reach as high as 6,473 cancellations per execution in 2008. This ratio has trended down though, along with the overall number of quote stuffing episodes.

The Securities and Exchange Commission (SEC) estimates an average of 17.61 cancellations per trade for all stocks traded on Nasdaq in 2012 and 19.49 in 2013.[4] These indicate the extreme stress than quote stuffing places on the order book.

A broader measure is the number of inside quote updates required to execute a trade. We compute this from TAQ for all exchanges, including Nasdaq for common stocks

[INSERT Table 5 HERE: Inside Quote to Trade Ratio - Common Stocks]

Inside quotes on TAQ show a similar pattern to Nasdaq total message activity. On Nasdaq, there are an average of 23 times more inside quotes per trade in a 90th percentile stock.

5. Market Quality on Other Exchanges

Given the intense competition among exchanges, one might expect that quote stuffing on Nasdaq would simply lead to activity migrating to other exchanges. We find that market quality measures are effected on all the listing exchanges. We rely on TAQ data here which is not as comprehensive as ITCH. It provides only inside quotes and trades, and we don't know how quotes leave the book.

In Table 3, we also report the high-low range on the bid side in the minute after the quote burst on other listing exchanges, Amex, NYSE, and Arca. Compared to the same minute on the prior day, the 90th percentile volatility rises from 98.9 to 260.6 bps on Amex, from 32.0 to 54.9 bps on NYSE, and from 46.6 to 110.8 bps on Arca during the sample period from 2008-2016. The Wilcoxon signed rank test rejects the null hypothesis of equal volatility at the 16.32 standard deviation level or greater in each year for any of the three exchanges.

The average bid-ask spreads on other listing exchanges are presented in Table 4 as well. During

[4] Cancellation to execution ratios are much higher on ETFs, 71.54 in 2012 and 68.70 in 2013.

the minute after a quote stuffing event the inside spread at the 90th percentile increases from 279.9 to 332.1 bps on Amex, from 56.9 to 67.4 bps on NYSE, and from 145.6 to 190.2 bps on Arca. The Wilcoxon tests reject at the 20.72 standard deviation level or higher.

We also compute the number of inside quote updates required to execute a trade on Amex, NYSE, and Arca, as shown in Table 5. The ratio of inside quote to trade rises dramatically in the minute after quote burst. For example, in 2010 it is as 152 times higher as the same minute on the prior day on Amex, 13 times higher on NYSE, and 18 times greater on Arca.

6. Trading Activity

We analyze trading volume in this section, measured both as the number of trades and also trading volume. Despite the high rate of cancellations during the quote stuffing episodes, volume actually rises on the Nasdaq and other exchanges, compared to the same time on the previous day. We think this has a strategic motivation, and we will show that trading volume is increasing in the number of high frequency cancellations.

We first illustrate the typical pattern of volume using data from April 23, 2013, which is graphed in Figure 4.

[INSERT Figure 4 HERE: Volume per Minute]

Volume, $V_{t,n}$, spikes along with the surge in cancellations and remains elevated for around five minutes after the event. We test for this rise in volume during the minute after quote stuffing across our entire sample in Table 6.

[INSERT Table 6 HERE: Trading Volume Per Minute]

We find that trading volume, $V_{i,t,n}$, spikes as well during quote stuffing episodes, and the pattern is consistent with trades. The Wilcoxon tests reject the null hypothesis of no volume difference at the 12.30 standard deviation level or greater for all the exchanges in each year from 2008-2016. Volume on Nasdaq and Arca rises the most at the 90th percentile. It averages nearly $four$ times higher on both Nasdaq and Arca.

Our finding contrast with the conjecture that a large number of cancellations would block trading activity. We want to explore whether our conclusion would change if there are extremely more cancellations on a stock. We run a screen for quote stuffing episodes with more than $100,000$

cancellations in one minute. We find 98 events that occurred on 42 stocks in April, June and August from 2010-2012. The most striking incident is Google (GOOG) on August 11, 2010 with $five$ occurrences and more than $330,000$ cancellations in each minute. The stock that experienced the highest number of episodes in the sample period is White Mountains Insurance (WTM) which experienced 28 bursts on April 19, 2010.

For each event, we compare the trading volume in the minute of a huge number of cancellations to the same minute on the prior day. Consistent with the conclusion for the quote stuffing sample, trading activity also rises during these episodes with an extremely high number of cancellations. The 90th percentile of volume increases from $3,060$ to $5,535$ on Nasdaq, from $2,500$ to $5,500$ on NYSE, and from $1,600$ to $3,454$ on Arca. The result for Amex is ambiguous because there are only two observations among these episodes. The Wilcoxon tests reject the null of no change at the *three* standard deviation level or higher for Nasdaq, NYSE, and Amex.

6.1 HFT volume

Our next step is to see whether we can attribute the increase in trading activity to HFT strategies. The first step is to examine whether HFT volume, $VC^{HFT}_{i,t,n} + VE^{HFT}_{i,t,n}$, rises during quote stuffing. We report the results in Table 7.

[INSERT Table 7 HERE: Increases in HFT volume]

Volume rises on average *seven* times during quote stuffing, with more than 15 times increases during events in 2013.

We then compare changes in aggregate HFT market share $V^{HFT}_{t,n}\%$,

$$V^{HFT}_{t,n}\% = \frac{VC^{HFT}_{i,t,n} + VE^{HFT}_{i,t,n}}{VC^{HFT}_{i,t,n} + VE^{HFT}_{i,t,n} + VC^{nHFT}_{i,t,n} + VE^{nHFT}_{i,t,n}}. \tag{6}$$

in the minute after the quote stuffing to the same minute in the same securities on the prior day, $V^{HFT}\%_{t,n-1}$. 90th percentiles of these ratios are reported in Table 8.

[INSERT Table 8 HERE: HFT Volume]

The HFT share of trading volume, at the 90th percentile, rises on average by 20%. The Wilcoxon test rejects equality of the distributions at the 71.72 standard deviation level or higher. It appears that HFT traders are driving non-HFT participants from the order book and capturing a larger market share of volume.

6.2 Zero volume hurdle

Many stocks have no volume and we use a hurdle model to describe these. The hurdle model consists of two parts: a zero model that separate the high occurrence of zeros from observed trades, and a linear model that predicts the non-zero volume. We use the HFT volume in the same minute on the prior day as a explanatory variable in the zero model. In the linear model we predict the volume of HFT executions in the minute of quote bursts using the number of cancellations. We report the model estimation for each year and the entire sample period from 2008-2016 in Table 9.

[INSERT Table 9 HERE: HFT Hurdle Model]

On average, 100 shares of HFT volume in the minute of quote stuffing on the prior day, $V_{t,n-1}^{HFT} = VC_{t,n-1}^{HFT} + VE_{t,n-1}^{HFT}$, results in a 29.8% probability of observing positive trading volume,

$$\Pr(V_{t+1,n}^{HFT} > 0 | V_{t+1,n-1}^{HFT} = 100) = 29.8\%. \tag{7}$$

The marginal effect is that each additional 1,000 cancellations, $\#CN_{t,n} = \#D_{t,n} + \#U_{t,n} + \#X_{t,n}$, are associated with 420 shares of HFT volume in the quote burst minute,

$$\mathrm{E}(V_{t,n}^{HFT} | V_{t,n-1}^{HFT} > 0, \#CN_{t,n} = \#CN_{t,n}^{0} + 1,000) - \mathrm{E}(V_{t,n}^{HFT} | V_{t,n-1}^{HFT} > 0, \#CN_{t,n} = \#CN_{t,n}^{0}) = 420. \tag{8}$$

The probability that HFT firms trade following a quote stuffing event has remained steady since 2008. In 2008, there is positive volume during quote stuffing in 40.2% of the events where at least 100 shares were transacted on the prior day. In 2013, this probability is 40.4%.

There is an additional externality from the active quoting of the HFT firms on the non-HFT participants. We study the choices of non-HFT firms in the next section.

6.3 Off-exchange activity

Trading activity appears to go off exchange when quote stuffing is occurring. We calculate the trading volume that goes to the Trade Reporting Facility (TRF) in Table 10.

[INSERT Table 10 HERE: TRF Market Share of Volume]

These trades are recorded in TAQ and include both dark pool and internalized trades. The TRF volume rises an average of 126% at the 90th percentile, from 3,150 to 7,170 shares during quote stuffing.

7. Market Wide Message Flows

This section first examines market wide message flows by aggregating all message traffic from ITCH. We then analyze the impact on the intermarket communication lags on the Securities Information Processor (SIP).

7.1 Aggregate message volume

We first tabulate the aggregate number of messages of all kinds in ITCH. Daily averages are plotted in Figure 5.

[INSERT Figure 5 HERE: Estimates of ITCH Message Traffic]

Message traffic appears to have peaked in 2011 with an average of 383 million messages per day on ITCH. Daily averages fell in 2012 and 2013, declining to 238 million per day on average in 2013. ITCH messages have started to trend back up again, reaching an average 298 million per day in 2016.

Despite a slowdown in average activity, the market continues to experience new peak message volumes, as shown in Figure 6, in one-minute message frequency.

[INSERT Figure 6 HERE: Peak ITCH Message Traffic]

The all time high for our sample from 2008-16 occurs on April 23, 2013 at 13:10, when more than 8.2 million messages are transmitted. That is the day that the Associated Press Twitter feed was hacked, and there was an erroneous report of an attack on the White House.

7.2 SIP Externalities

The equity market is quite special in that it provides investors with a best execution standard. The exchanges are required to determine the national best bid and offer (NBBO), and all trading venues must either route to the exchange with the best quote or offer some price improvement.

Exchange communicate to one another using a relatively slow inter-market messaging system known as the Securities Information Processor (SIP). HFT strategies do not rely on the SIP, and they compute their own private NBBO for routing purposes. Ding, Hanna and Hendershott

(2014) document multiple dislocations each second between the NBBO and direct exchange feeds for active stocks. These dislocations are short, generally one to two milliseconds, but they are potentially costly to HFT traders. There are occassions though when the lags grow much longer. The Flash Crash of May 6, 2010 is one such example.

Effective from August 3, 2015, the daily TAQ data includes a new Participant Timestamp field in the precision of microseconds. We utilize this data to calculate the time lag between the quotes in TAQ and what participants provided, which gives us SIP delays in both Nasdaq and non-Nasdaq listings.[5]

In our statistical analysis, we measure latency as the maximum time difference between the direct exchange feed and the SIP in stock i in minute t on day n. The explanatory variables are the aggregate message traffic in ITCH, and a dummy variable for quote stuffing events which picks up the activity in a given symbol by HFT firms,

$$Latency_{i,t,n} = \alpha + \beta_1(\#M_{t,n}^{HFT} + \#M_{t,n}^{nHFT}) + \beta_2 I(zM_{i,t,n}^{HFT} \geq 30) \times \#M_{i,t,n}^{HFT} \tag{9}$$

We estimate this model for each stock, on each day, that a quote stuffing event occurs in that symbol. We report, in Table 11, the average number of messages needed to raise latency by one milisecond,[6] and the number of significant coefficients, along with the average adjusted R^2. We separate the results by exchange, grouping the Nasdaq symbols in one panel, and the non-Nasdaq in another.

[INSERT Figure 6 HERE: Aggregate ITCH Message Peaks]

Across all quote stuffing events, quote stuffing incidents are significant 15.3% for Nasdaq listed stocks, and 14.8% for non-Nasdaq listings in 2015. These effects are similar in 2016, 11.3% for Nasdaq and 13.9% for non-Nasdaq.

Across all exchanges, it takes less than 700 HFT messages to delay the SIP by one millisecond during a quote stuffing incident in 2015. It takes at least $60,000$ aggregate messages to have the same effect.

With the recent interest in cases like Sarao, where traders repeatedly display and cancel buying and selling interest, we focus on cases where there are more than five events in a symbol during the trading day. These events, nearly $1,700$ in 2015 and $1,600$ in 2016, are more frequently linked

[5] We have also measure the time lag between the exchange time stamp and the dissemination time of quotes in the Thomson Reuters trading system (TRTH). This measure produces very similar qualitative conclusions.
[6] The values for β_1 and β_2 can be obtained by dividing 0.001 by the numbers in the table.

to delays in the SIP. They are significant 30% of the time in 2015 and 26% in 2016.

It is difficult to quantify the harm to market quality caused by the SIP delays. Qualitiatively, we know that SIP delays result in orders being incorrectly routed away to exchanges that don't have the best prices. When traders can no longer trust the prices they see on their trading screens, it also reduces confidence in the market.

8. Conclusion

Rapid submission and cancellation strategies by high-frequency trading (HFT) firms are a common occurrence, effecting hundreds of ticker symbols every day. We find that quote stuffing is harmful to market quality: prices become more volatile and bid-ask spreads rise. This occurs not only on the Nasdaq where we observe the quote stuffing, but also on the NYSE, Archipelago and Amex. HFT quote stuffing raises their market share of trading activity. We estimate that $1,000$ high frequency cancellations generate an average of 420 HFT volume in the next minute. Rapid cancellations drive trading activities to non-exchange trading venues, with the median TRF volume that doubles during quote stuffing. Aggregate message activity in the equity markets has stabilized, but there are still sporadic episodes of message bursts that pose operational risks for the markets. We can tie these episodes directly into latency lags in the inter-market pricing system.

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Table 1: ITCH Message Description

Messages that Add Liquidity	
A	Add w/o MPID
F	Add w/ MPID
Delete, Cancel, or Replace	
D	Deletion
U	Cancel and replace
X	Partial cancellation
Executions	
C	At different price
E	At linked order price

For a more complete description, please read the documentation with the releases of the Nasdaq ITCH Total View data set, versions 3.0, 3.1, 4.0 and the current 4.1, available at http://www.nasdaqtrader.com/Trader.aspx?id=itch.

Table 2: **Characteristics of Stocks Experiencing Quote Stuffing**

	Average		Listing Exchange				Share Types		
Year	**Volume**	**Mkt cap $bn**	**NYSE**	**Nasdaq**	**Amex**	**Arca**	**Common**	**ETFs**	**Other**
2008	1,650,149	2.734	41.64%	23.81%	4.02%	30.54%	49.01%	30.01%	20.98%
2009	2,042,369	1.751	28.25%	41.07%	3.56%	27.12%	54.16%	29.14%	16.69%
2010	1,369,771	1.644	27.32%	40.46%	3.08%	29.14%	51.93%	28.69%	19.38%
2011	1,102,990	1.859	22.55%	47.07%	2.89%	27.49%	55.78%	27.23%	17.00%
2012	1,358,948	2.637	29.97%	46.48%	2.40%	21.15%	58.29%	20.97%	20.75%
2013	1,701,716	3.187	23.40%	44.16%	2.83%	29.61%	48.28%	29.80%	21.92%
2014	1,822,990	4.266	36.91%	31.59%	4.54%	26.95%	40.03%	28.97%	31.00%
2015	1,769,518	4.018	30.28%	32.17%	2.90%	34.65%	39.96%	38.61%	21.44%
2016	2,103,486	1.228	29.86%	54.21%	1.00%	14.93%	65.52%	18.00%	16.48%

The table reports characteristics of stocks experiencing quote stuffing events in the Nasdaq Totalview ITCH data. The volume, market capitalization, listing exchange data and share types are from CRSP on the first day of the month.

Table 3: Bid Price Range After Quote Stuffing Events
90th Percentile

	Nasdaq		**Amex**		**NYSE**		**Arca**	
Year	$HL_{t+1,n}$	$HL_{t+1,n-1}$	$HL_{t+1,n}$	$HL_{t+1,n-1}$	$HL_{t+1,n}$	$HL_{t+1,n-1}$	$HL_{t+1,n}$	$HL_{t+1,n-1}$
2008	0.928%	0.594%	0.619%	0.389%	0.637%	0.436%	0.879%	0.550%
2009	1.570%	0.658%	1.126%	0.899%	0.662%	0.476%	1.342%	0.625%
2010	1.753%	0.581%	3.529%	1.880%	0.697%	0.378%	1.907%	0.642%
2011	1.860%	0.600%	1.502%	0.869%	0.618%	0.352%	1.739%	0.606%
2012	0.892%	0.287%	1.980%	0.662%	0.453%	0.238%	0.894%	0.328%
2013	0.720%	0.233%	4.857%	1.101%	0.454%	0.201%	0.783%	0.254%
2014	0.721%	0.250%	4.216%	0.820%	0.476%	0.222%	0.734%	0.294%
2015	0.859%	0.303%	2.161%	0.549%	0.475%	0.271%	0.994%	0.411%
2016	0.725%	0.366%	3.464%	1.730%	0.471%	0.305%	0.703%	0.479%

The table reports the 90th percentile of the high-low bid range, $HL_{t+1,n}$ during the minute after the quote stuffing event at time $t+1$ on day n, compared to the same security at time $t+1$ on the prior day, $n-1$. We perform Wilcoxon signed rank tests for equality of the distributions. Test statistics are normally distributed, and all the tests reject at the 16.32 standard deviation level or higher.

Table 4: Percentage Bid-Ask Spread After Quote Stuffing Events
90th Percentile

	Nasdaq		**Amex**		**NYSE**		**Arca**	
	$S_{t+1,n}$	$S_{t+1,n-1}$	$S_{t+1,n}$	$S_{t+1,n-1}$	$S_{t+1,n}$	$S_{t+1,n-1}$	$S_{t+1,n}$	$S_{t+1,n-1}$
2008	0.907%	0.778%	1.937%	1.627%	0.543%	0.436%	0.851%	0.728%
2009	2.141%	1.709%	2.062%	1.966%	0.882%	0.762%	2.552%	1.796%
2010	2.152%	1.618%	5.956%	5.081%	0.973%	0.786%	2.669%	1.869%
2011	3.052%	2.173%	3.101%	2.782%	1.176%	0.861%	3.325%	2.293%
2012	1.619%	1.321%	2.299%	1.993%	0.533%	0.457%	2.415%	1.910%
2013	0.963%	0.845%	2.916%	2.643%	0.458%	0.407%	1.534%	1.307%
2014	0.892%	0.686%	3.558%	2.955%	0.404%	0.356%	0.957%	0.844%
2015	1.063%	0.801%	2.982%	1.989%	0.538%	0.500%	1.422%	1.131%
2016	1.126%	1.000%	5.075%	4.156%	0.563%	0.560%	1.389%	1.224%

The inside bid-ask spreads are from the NYSE Trade and Quote Database. The table reports the 90th percentile of the percentage bid-ask spread, $S_{t+1,n}$ during the minute after the quote stuffing event at time $t+1$ on day n, compared to the same security at time $t+1$ on the prior day, $n-1$.We perform Wilcoxon signed rank tests for equality of the distributions. Test statistics are normally distributed, and all the tests reject at the 20.72 standard deviation level or higher.

Table 5: Inside Quotes Per Trade After Quote Stuffing Events
90th Percentile

	Nasdaq		**Amex**		**NYSE**		**Arca**	
	$QT_{t+1,n}$	$QT_{t+1,n-1}$	$QT_{t+1,n}$	$QT_{t+1,n-1}$	$QT_{t+1,n}$	$QT_{t+1,n-1}$	$QT_{t+1,n}$	$QT_{t+1,n-1}$
2008	3556	262	173	86	277	134	1299	228
2009	4734	273	42	23	398	156	1087	180
2010	6653	167	181	37	1478	192	2502	164
2011	6255	215	174	33	1521	201	2016	192
2012	4039	194	107	28	729	216	543	111
2013	2900	171	158	27	747	224	835	95
2014	1650	74	107	32	358	120	415	66
2015	2448	71	394	46	512	91	949	68
2016	1034	64	85	44	276	83	390	60

The source is the NYSE Trade and Quote Database using share codes from CRSP. The table reports the 90th percentile of the ratio of inside quotes per trade, $QT_{t+1,n}$ during the minute after the quote stuffing event at time $t+1$ on day n, compared to the same security at time $t+1$ on the prior day, $n-1$.We perform Wilcoxon signed rank tests for equality of the distributions. Test statistics are normally distributed, and all the tests reject at the 19.18 standard deviation level or higher.

Table 6: Trading Volume Per Minute After Quote Stuffing Events
90th Percentile

	Nasdaq		**Amex**		**NYSE**		**Arca**	
	$V_{t+1,n}$	$V_{t+1,n-1}$	$V_{t+1,n}$	$V_{t+1,n-1}$	$V_{t+1,n}$	$V_{t+1,n-1}$	$V_{t+1,n}$	$V_{t+1,n-1}$
2008	4052	2900	2400	1400	3500	2700	3000	2100
2009	5515	3900	1500	1000	3900	3100	4303	3000
2010	3150	1800	600	400	3100	2300	2600	1500
2011	4166	1800	600	400	2500	1700	3200	1400
2012	7600	1698	2400	400	5454	1801	5406	1300
2013	13833	1600	3012	400	7234	1700	10400	1300
2014	16300	2000	3200	500	12900	2002	9600	1300
2015	4780	1400	3471	800	3305	1406	4200	1237
2016	5000	2131	2600	1100	9063	2875	4240	1347

The source is the NYSE Trade and Quote Database. The table reports the 90th percentile of trading volume $V_{t+1,n}$ during the minute after the quote stuffing event at time $t+1$ on day n, compared to the same security at time $t+1$ on the prior day, $n-1$.We perform Wilcoxon signed rank tests for equality of the distributions. Test statistics are normally distributed, and all the tests reject at the 12.30 standard deviation level or higher.

Table 7: High Frequency Trading Volume on Nasdaq
90th Percentile

	$V_{t,n}^{HFT}$	$V_{t,n-1}^{HFT}$
2008	1220	700
2009	1517	959
2010	1600	600
2011	1701	600
2012	3198	500
2013	6601	417
2014	6817	500
2015	3480	492
2016	5284	523

The source is the Nasdaq Totalview ITCH data. The table reports the 90th percentile of HFT trading volume $V_{t,n}^{HFT}$ during the minute after the quote stuffing event at time t on day n, compared to the same security at time t on the prior day, $n-1$.We perform Wilcoxon signed rank tests for equality of the distributions. Test statistics are normally distributed, and all the tests reject at the 76.07 standard deviation level or higher.

Table 8: Proportion of High Frequency Volume on Nasdaq
90th Percentile

	$V_{t,n}^{HFT}\%$	$V_{t,n-1}^{HFT}\%$
2008	51.78%	33.33%
2009	47.16%	33.33%
2010	56.03%	33.33%
2011	63.27%	41.89%
2012	52.00%	33.33%
2013	60.58%	33.33%
2014	60.00%	36.60%
2015	73.53%	48.53%
2016	60.89%	49.26%

The source is the Nasdaq ITCH Totalview Database. The table reports the 90th percentile of HFT market share of volume $V_{t,n}^{HFT}\%$ during the minute after the quote stuffing event at time t on day n, compared to the same security at time t on the prior day, $n-1$.We perform Wilcoxon signed rank tests for equality of the distributions. Test statistics are normally distributed, and all the tests reject at the 71.72 standard deviation level or higher.

Table 9: Regression Model for Effect of Cancellations on Trades

	Logit		OLS		
	Intercept	$V^{HFT}_{t,n-1}$ ($\times 10^{-3}$)	Intercept	$\#CN_{t,n}$	R^2
2008	-0.66	0.85	-195.09	0.31	2.81%
	(0.01)	(0.02)	(61.84)	(0.01)	
2009	-1.06	0.85	485.27	0.19	2.96%
	(0.01)	(0.01)	(33.13)	(0.00)	
2010	-1.43	0.83	-186.72	0.66	5.98%
	(0.01)	(0.02)	(102.21)	(0.01)	
2011	-1.42	1.50	1199.21	0.11	0.44%
	(0.01)	(0.02)	(68.21)	(0.01)	
2012	-0.95	1.02	543.71	0.96	4.18%
	(0.01)	(0.02)	(82.14)	(0.02)	
2013	-0.61	0.70	-6717.45	6.66	30.51%
	(0.01)	(0.03)	(198.50)	(0.07)	
2014	-0.49	1.20	1328.05	1.38	4.82%
	(0.01)	(0.04)	(111.30)	(0.04)	
2015	-1.32	1.17	-3009.69	3.40	10.76%
	(0.01)	(0.05)	(286.20)	(0.09)	
2016	-0.71	1.44	1667.02	1.06	3.95%
	(0.01)	(0.05)	(150.10)	(0.04)	
All	-1.07	1.02	962.76	0.42	2.42%
	(0.00)	(0.01)	(31.47)	(0.00)	

The table reports the estimates and t-statistics of the hurdle model for each year from 2008-2015. There are two parts in a hurdle model: a logit model and a linear regression model. The dependent variable is the HFT volume in the minute during quote bursts, $V^{HFT}_{t,n} = VC^{HFT}_{t,n} + VE^{HFT}_{t,n}$. In the logit model, we use high frequency trading volume in the previous day $V^{HFT}_{t,n-1}$ as a explanatory variable. The independent variable in the linear model is the number of cancellations in the minute of quote stuffing, $\#CN_{t,n} = \#D_{t,n} + \#U_{t,n} + \#X_{t,n}$. Numbers in parenthesis are the standard error of coefficient estimates.

Table 10: Off-Exchange Trading Volume During Quote Stuffing Events
90th Percentile

	$V^{TRF}_{t+1,n}$	$V^{TRF}_{t+1,n-1}$
2008	3500	2600
2009	5400	4187
2010	3900	2700
2011	4378	2700
2012	6850	2800
2013	12933	3364
2014	14991	3600
2015	5127	2500
2016	7454	3493

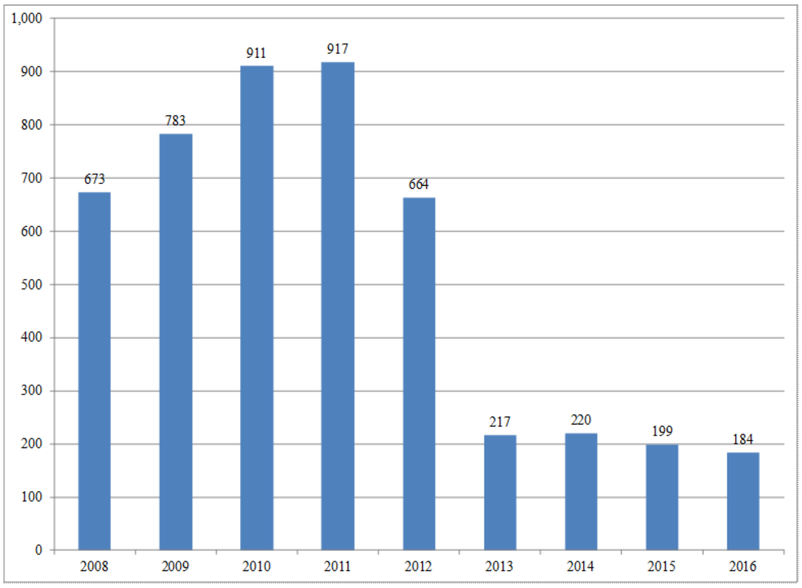
The table reports the 90th percentile of the market share of volume recorded in the trade reporting facility (TRF) from NYSE TAQ data during the minute after the quote stuffing event at time t on day n, compared to the same security at time t on the prior day, $n-1$. We perform Wilcoxon signed rank tests for equality of the distributions. Test statistics are normally distributed, and all the tests reject at the 86.74 standard deviation level or higher.

Table 11: Estimation of Latency Model

	Number of Messages to Increase Latency by 1 msec		% of statistically significant regresssors		
Nasdaq	Aggregate	Quote Stuffing	Aggregate	Quote Stuffing	$\overline{R}^2$
2015	123,718	682.14	96.07%	15.34%	11.57%
2016	130,601	548.44	95.35%	11.32%	10.03%
non-Nasdaq	Aggregate	Quote Stuffing	Aggregate	Quote Stuffing	$\overline{R}^2$
2015	57,250	214.89	98.12%	14.83%	14.88%
2016	65,706	152.74	96.99%	13.88%	11.67%
Nasdaq>=5	Aggregate	Quote Stuffing	Aggregate	Quote Stuffing	$\overline{R}^2$
2015	90,003	515.64	95.85%	28.63%	14.57%
2016	173,421	875.10	93.11%	25.74%	10.51%
non-Nasdqa>=5	Aggregate	Quote Stuffing	Aggregate	Quote Stuffing	$\overline{R}^2$
2015	55,868	150.33	96.99%	33.11%	15.26%
2016	64,317	320.12	94.90%	27.20%	13.08%

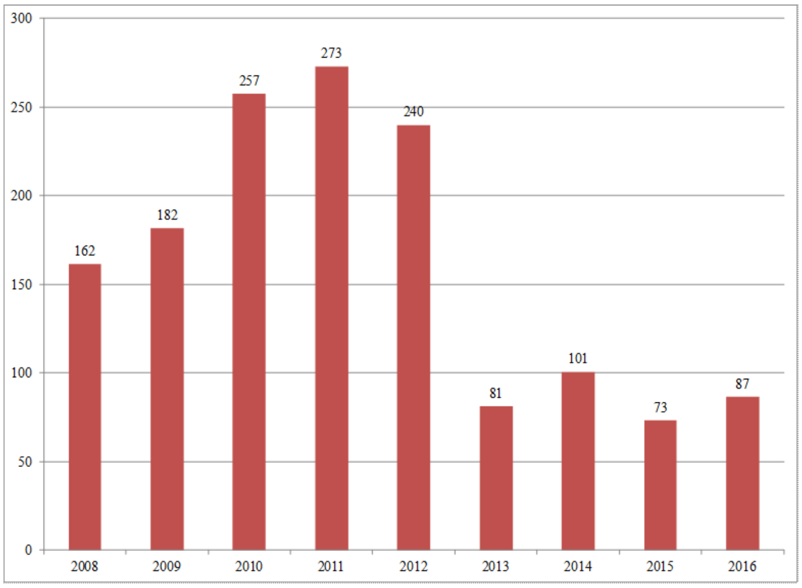
The table reports annual estimates of the latency in the Securities Information Processor (SIP) using the model (9). The first variable is the aggregate message traffic in all symbols ($\#M_{t,n}^{HFT} + \#M_{t,n}^{nHFT}$). The second variable is the HFT message count in that symbol during a quote stuffing episode, $I(zM_{i,t,n}^{HFT} \geq 30) \times \#M_{i,t,n}^{HFT}$. The coefficients in column (2) and (3) of table are the average of the marginal effects of all the cross section regressions. The number reported is the average number of messages needed to increase latency by one millisecond. To obtain the $\beta's$ divide 0.001 by the number in the Table. Columns (4) and (5) report the number of statistically significant positive coefficients. Column (6) is the average $\overline{R}^2$. The second set of estimates restricts the sample to cases where there are five or more events in a symbol on a given day.

Figure 1: Quote Stuffing Events
Daily Averages



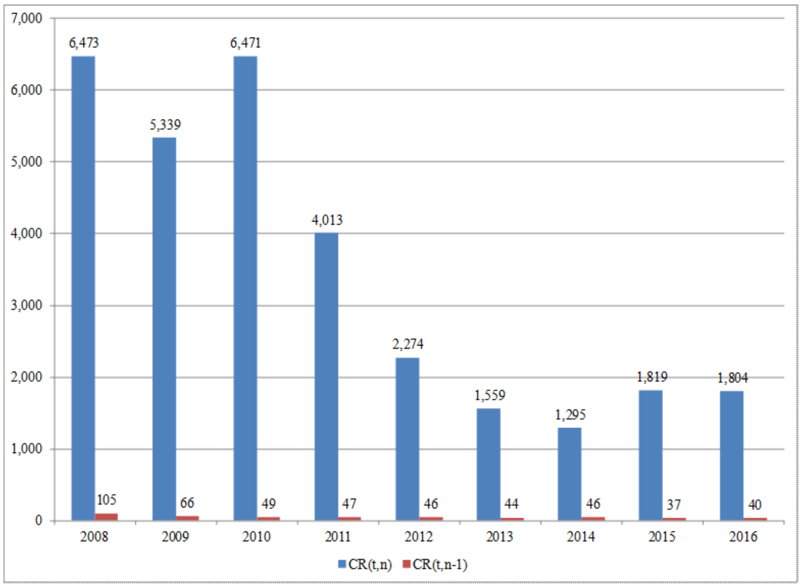
A quote stuffing event occurs when there is a 30-standard deviation increase in the high frequency cancellation rate compared to the rate for that symbol on the prior day. A stock can experience multiple events during the day, and there can be quote stuffing on both the bid and ask. Cancellations are computed using order level data from Nasdaq Totalview ITCH.

Figure 2: Symbols Experiencing Quote Stuffing
Daily Averages



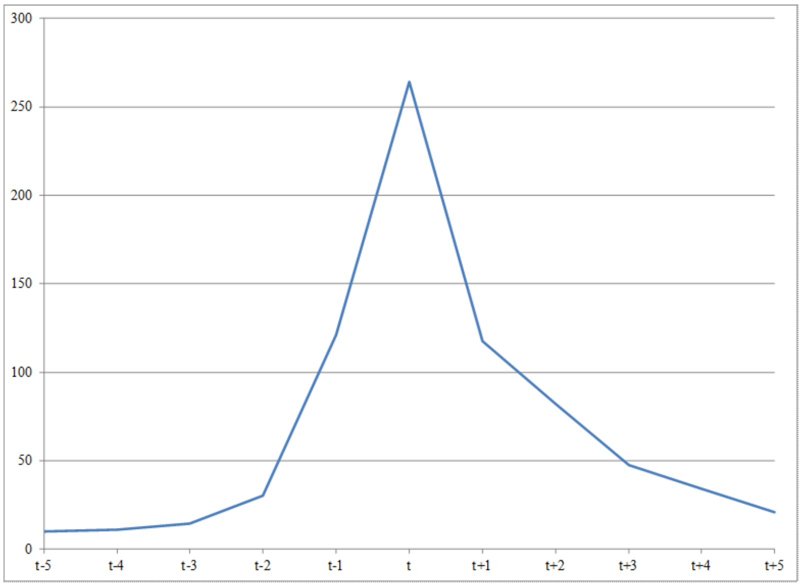
A quote stuffing event occurs when there is a 30-standard deviation increase in the high frequency cancellation rate compared to the rate for that symbol on the prior day. Cancellations are computed using order level data from Nasdaq Totalview ITCH.

Figure 3: Cancellation to Execution Ratio During Quote Stuffing Events 90th Percentile



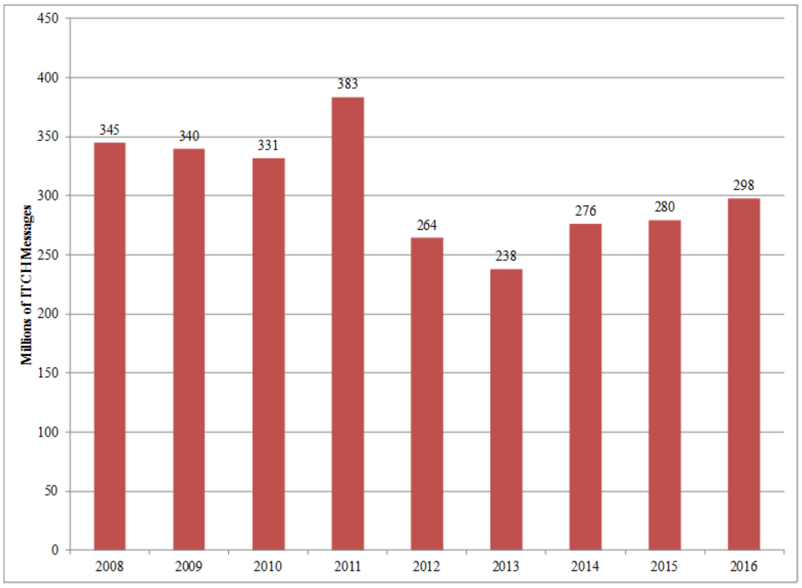
A quote stuffing event occurs when there is a 30-standard deviation increase in the high frequency cancellation rate compared to the rate for that symbol on the prior day. Cancellations are computed using order level data from Nasdaq Totalview ITCH. This chart reports the 90th percentile of cancellation to execution ratio $CR^{HFT}_{i,t,n} = (\#D^{HFT}_{i,t,n} + \#U^{HFT}_{i.t,n} + \#X^{HFT}_{i.t,n})/(\#C^{HFT}_{i,t,n} + \#E^{HFT}_{i,t,n})$, of all trades, in the minute after the quote stuffing, $CR_{t,n}$ against the prior day's ratio for those same securities, $CR_{t,n-1}$. The Wilcoxon test for median differences rejects at the 185.40 standard deviation level or higher.

Figure 4: Trades per Minute During Quote Stuffing Events
90th Percentile



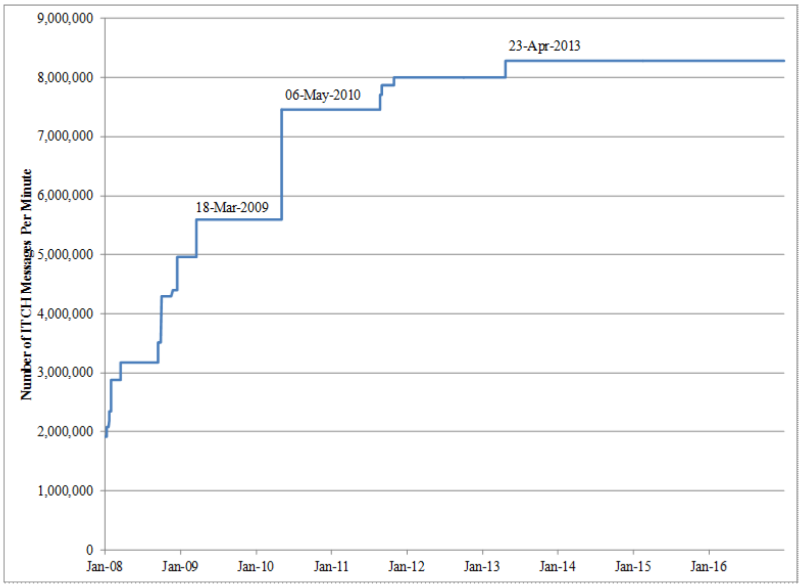
The chart depicts trading activity for the day of April 23, 2013 during quote stuffing events at time t and for five periods before and after. We examine the 10% most actively traded stocks.

Figure 5: Total ITCH Message Traffic
Daily Averages



The chart reports averages of aggregate daily ITCH message traffic.

Figure 6: Growth in Message Traffic on Nasdaq
One-Minute Peaks



The chart reports local maxima of one minute aggregate daily ITCH message traffic.