Did the Introduction of ETPs Change the Intraday Price Dynamics of VIX Futures?

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Abstract

We examine the impact of the introduction of VIX Exchange Traded Products (ETPs) on the information content and pricing efficiency of VIX futures. We document that trades have become less informative and pricing errors have shown more persistence after the introduction of VIX ETPs. In addition, we observe that the price process of the VIX futures has become noisier over time. These findings suggest that the introduction of the VIX ETPs had a prominent effect on the intraday properties and dynamics of the VIX futures, and shed light on the price efficiency of VIX futures.

Keywords: VIX Futures, VIX, market microstructure, Kalman Filter

JEL Codes: C22, G13.

1. Introduction

Exchange-traded products (ETPs) are increasingly popular among retail investors. Managers of ETPs often use futures contracts to manage their risk exposure as demand from retail investors changes. Bollen, O'Neill and Whaley (2013) document that excessive liquidity demand from VIX ETPs sometimes drives VIX futures prices or as they call it the "tail is wagging the dog". This paper examines whether the introduction of ETPs on the volatility index (VIX) changed the intraday price dynamics of VIX futures due to hedging pressure by managers of ETPs.

Although VIX futures were introduced by the Chicago Board Options Exchange (CBOE) on March 26, 2004, VIX futures trading volume was rather limited until the introduction of VIX options on February 24, 2006. However, arguably what really led to popularity and major uptake in VIX futures trading volume was the introduction of several VIX ETPs. These products, tracking an index based on VIX futures, made the trading of volatility widely accessible to retail investors. The first ETPs were the VXX and the VXZ (introduced by Barclays Bank PLC on January 29, 2009) which track the S&P 500 VIX Short-term and Medium-term Futures index, respectively. As these ETPs track a VIX futures index, the ETP provider needs to hedge its positions in the underlying and trade in the VIX futures accordingly. Increased demand for ETPs by retail investors led to a large increase in the trading volume in the VIX futures, to such a high level that the demand for VIX futures from ETPs at times exceeded the open interest in the VIX futures (Bollen et al., 2013)

The VIX ETP market is large reaching approximately $US 2 billion invested in these ETPs. The market for VIX futures is large as well, with over 200,000 contracts traded per month in January of 2014. In fact, VIX derivatives are the second-largest contributor to the profits of the Chicago Board Options Exchange, after options on the S&P500 stock index.

In this paper, we are particularly interested in investigating the market microstructure properties of the VIX futures, focusing on the first and second nearby futures contracts. These contracts are by far the most heavily traded and also are the most demanded by VIX ETPs.

We build a state space model for the intraday price dynamics based on Brogaard et al. (2014) and Hendershott and Menkveld (2014), which we model in transaction time. This model allows us to assess the intraday price dynamics of the VIX futures and comment study on the informativeness or price impact of trades. More importantly, this model allows us to decompose the price process of the VIX futures into a permanent part (representing the efficient price process) and a transitory part (representing temporary deviations from the efficient price) and assess the properties of both processes. Empirically, we estimate our model using a Kalman Filter technique over the period before (24 February 2006 to 28 January 2009) and after (29 January 2009 to 2 September 2014) the introduction of the VIX ETPs.

Our results show that the price impact (or informativeness) of order flow for the evolution of the efficient price has decreased over time, as has the contribution of order flow to the variance of the efficient price process. For the transitory part, we find that order flow, in general, is in the opposite direction of the pricing error (a finding that is in line with Brogaard et al., 2014). However, this correction of the pricing error declines over time, suggesting that there is less correction occurring in the period after the introduction of the VIX ETPs. In addition, we observe that there is persistence in the pricing error, suggesting that price pressures persist. Over time, we observe an increase in persistence, again suggesting that after the introduction of the VIX ETPs pricing errors persist longer. Finally, when we compute the ratio of the variance of the efficient price to the variance of the observed price (efficient price plus transitory component) we find that this ratio has declined over time, indicating price movements of the VIX futures reflect less the movements in the efficient price and, we conjecture, are more driven by noise.

We further assess the properties of the VIX futures intraday in the two subperiods and observe that the introduction of the VIX ETPs had an impact on the intraday properties of these contracts as well. For instance, we find that the persistence in the pricing error declines towards the end of the trading day in the period before the introduction of the VIX ETPs, but increases towards the end of the trading day after the introduction of the VIX ETPs. This may be a consequence of VIX ETPs rebalancing their positions mostly towards the end of the trading day.

Lastly, we document that the price process for the VIX futures is more informative on high volatility days versus low volatility days. Specifically, we observe that on high volatility days, trades have a stronger impact in reducing the pricing error, while the persistence in the pricing error is lower. Overall, this causes the contribution of the efficient price process to the variance of the total price process to be considerably higher on high volatility days than on low volatility days.

The remainder of this paper is structured as follows. In section 2, we provide a literature review. We develop the model for the intraday dynamics of VIX Futures prices in Section 3. Section 4 details the data and documents summary statistics. In section 5, we present the results of our analysis. Finally, section 6 concludes.

2. Literature

VIX futures were introduced by the CBOE on March 26, 2004. The introduction of VIX futures for the first time made expected short-term volatility a tradeable product. Following the introduction of these products several studies emerged looking into the pricing of the VIX futures. Since the underlying of the VIX futures is not a tradeable product, pricing these futures cannot easily be done on the basis of arbitrage arguments (see, e.g, Zhu and Lian, 2012; Lu and Zhu, 2010; Brenner, Shu and Zhang, 2008, Lin, 2007, Zhang and Zhu, 2006, among others). These studies essentially differ in the assumptions they make about the properties of the process for the VIX. For instance, Zhang and Zhu (2006) build on the Heston (1993) model, allowing the volatility process to be mean-reverting. They find that their pricing model overprices futures contracts between 16% to 44%. More recently, Zhu and Lian (2012) explore the pricing properties of a model that allows for both jumps in the asset price and the volatility process to derive a closed-form pricing formula for the VIX futures. They show that it is mainly the addition of jumps to the asset price process that leads to improvements in pricing of the VIX futures.

Another branch of research has studied whether the VIX futures have diversification benefits, and therefore improve risk-adjusted returns. Daigler and Rossi (2006) and Szado (2009) document that relatively small positions in VIX futures can lead to considerable improvements in risk reduction and return enhancement.

A third line of research addresses the question of predictability of VIX futures. For instance, Konstantinidi, Skiadopoulos and Tzagkaraki (2008) propose and test several models to forecast implied volatilities. While they observe that there is predictability in implied volatilities, they document that a trading strategy using VIX futures cannot exploit this predictability in an economic sense. In a follow-up study, Konstantinidi and Skiadopoulos (2011) directly address the question whether VIX futures are predictable. Similar to Konstantinidi et al. (2008), they reach the conclusion that while there is predictability in a statistical sense, but it cannot be exploited in an economic sense either.

More recently, the literature has focused on the intraday properties and intraday dynamics of VIX and VIX futures. Frijns, Tourani-Rad and Webb (2015), for instance, address the question who leads in terms of reflecting volatility first, the VIX or the VIX futures. Using intraday data sampled at a 15-second frequency, they document that the informational role of the VIX futures has increased over time to a stage where they are informationally dominant over the VIX. In a related study, Fernandez-Perez, Frijns and

Tourani-Rad (2015) examine the intraday patterns in the VIX and its futures around Federal Open Market Committee (FOMC) announcements. The authors document that VIX and VIX futures display a gradual decline lasting for about 45 minutes following the FOMC announcement. Bailey, Zheng and Zhou (2014) also provide a detailed study on the intraday properties of the VIX and confirm its mean-reverting properties even at an intraday frequency.

Our paper fits well into this most recent strand of research, where our aim is to understand the microstructure properties of the VIX futures. Examination of these properties is of particular interest following the introduction of VIX ETPs which according to Bollen et al. (2013) and media[1] may have had a considerable impact on the dynamics of VIX Futures. We thus fill in an important gap in analyzing these properties and investigating potential changes in the properties due to the developments in the VIX ETP market.

3. Model

To examine the intraday dynamics in the VIX Futures contracts, we estimate a state space model similar to Brogaard et al. (2014) and Hendershott and Menkveld (2014). We do this by decomposing the VIX futures price into two components, a non-stationary price process that captures the evolution of the efficient price, and a transitory or stationary process that captures temporary deviations from the efficient price, i.e.

[1]http://blogs.barrons.com/focusonfunds/2015/09/17/vix-etfs-tails-that-wag-the-dog/

$$p_t = m_t + s_t, \tag{1}$$

where p_t is the log midquote at the time of a trade occurring at time t, m_t is the unobserved efficient price of the asset, and s_t captures the temporary deviations from the efficient price. The efficient or permanent price component is modeled as a random walk with respect to the arrival of information, where information can either be from public news shocks or from private information.[2] Hence, the efficient price process can be written as

$$m_t = m_{t-1} + \lambda \hat{O}_t + \varepsilon_t, \tag{2}$$

where $\hat{O}_t$ is the surprise in order flow (in number of contracts) of the t^{th} transaction in a given day, and ε_t captures the arrival of news that is not related to trade. The price impact of the surprise in order flow is captured by λ, and can be seen as a measure of private information held by traders in the VIX futures. We capture the surprise in order flow by taking the residuals of an autoregressive model regression of signed order flow.

For the transitory component, we assume trades can exert a temporary price pressure that pushes the price temporarily away from their efficient price. This happens through the signed order flow O_t, and to capture some persistence in the price pressure, we model the transitory component as an AR(1), i.e.,

[2]Like Brogaard et al. (2014), we do not include a drift term in the efficient price process as sampling is done in transaction time. At this high-frequency the price drift would be extremely small.

$$s_t = \varphi s_{t-1} + \theta O_t + \eta_t \ , \tag{3}$$

where φ captures the persistence in the price pressure, θ captures the effect of order flow on the transitory component and η_t captures shocks to the temporary component. Similar to Brogaard et al. (2014) and Hendershott and Menkveld (2014), we assume that the innovations in the efficient price process and the transitory components are independent, i.e. Cov(ε_t, η_t) = 0. This can be done because we include order flow in both the efficient price process as well as the transitory component. This inclusion eliminates the correlation between the innovations of the permanent and transitory components.

Presenting these equations together, we estimate the following state space model:

$$\begin{cases} p_t = m_t + s_t \\ m_t = m_{t-1} + \lambda \hat{O}_t + \varepsilon_t \\ s_t = \varphi s_{t-1} + \theta O_t + \eta_t \end{cases} \tag{4}$$

Given that the permanent component of the price process follows a random walk, we initialize the Kalman Filter using a diffuse prior. Estimation of the model is done day-by-day using maximum likelihood via the Kalman Filter.

4. Data

We obtain intraday data for the VIX futures from the Thomson Reuters Tick History (TRTH) database maintained by SIRCA (Securities Industry Research Centre of Asia-Pacific). We collect tick-by-tick data time-stamped to the nearest millisecond. Although the VIX futures were introduced on 26 March 2004, they were rather illiquid until the introduction of the VIX options on 24 February 2006. Hence, we limit the sample from 24 February 2006 to 2 September 2014. We obtain both trade and quote data for all VIX futures contracts. The VIX futures contracts have maturities at every month of the year. However, we focus on the first and second nearby contracts because they are by far the most heavily traded ones, and also are the most demanded by VIX ETPs. As in Shu and Zhang (2012), we roll to the next nearest maturity on the day when the current first nearby contract expires. This is in line with what the ETPs issuers do. The ETP issuers employ a roll period which starts on the VIX futures settlement date (generally a Wednesday) and ending with, but excluding, the following VIX settlement date (generally a Tuesday); see e.g. Bollen et al. (2013) and the VXX white paper.[3]

In Figure 1, we plot the evolution of the VIX over the sample period (upper part), along with the deviation of the VIX futures (first nearby: VXF1; and second nearby: VXF2) from the VIX (lower part). The VIX displays a few well-known spikes due to the global financial crisis and subsequently due to the European debt crisis. We observe sharp increases in the VIX around these periods and a relatively slow mean-reversion afterwards.

Insert Figure 1 Here

[3]http://www.ipathetn.com/US/16/en/contentStore.app?id=5149530

When considering the lower part of Figure 1, where we plot the difference between the VIX futures and the VIX, we observe that the price differences are generally positive, i.e. the VIX futures are generally priced higher than the VIX, and that the second nearby contract typically plots above the first nearby contract. This reflects the generally upward sloping term structure for VIX futures (the so-called contango). However, we can see that when the VIX is high relative to its mean, the relation inverts and the VIX futures are priced below the VIX (known as backwardation).

Table 1 provides summary statistics on the VIX futures. To mitigate any confounding microstructure issues, we work with the midpoint of the bid and ask quotes. We report the statistics for the daily midquote price, daily close-to-close returns, the total daily volume, the total daily signed order flow[4], and the average percentage spread for the front end and second end VIX futures. For the first nearby VIX futures, the level price, on average, is 21.62, and has positive skewness and displays excess kurtosis. As common in level prices, the first-order autocorrelation is close to 1 and the Augmented Dickey-Fuller test does not reject the presence of a unit root. For the second nearby VIX futures, we observe that the average price level increases to 22.38.[5] In line with Figure 1, this result is well-documented in the literature (Szado, 2009; Shu and Zhang, 2012; Whaley, 2013; and Fernandez-Perez et al., 2015, among others), and is due to the term structure of VIX futures prices, on average, being in contango. The second nearby VIX

[4]Signed order flow is obtained as the total buy volume minus the total sell volume during the day where the trade indicator used to sign volume is based on Lee and Ready (1991).

[5]It should be noted that the underlying value of the VIX futures contract used to be VIX times 10 but on March 26, 2007, the underlying value was changed to be VIX and the futures price became one-tenth of the original value. Thus, we divided all prices and quotes in VIX futures before that date by 10.

futures present similar characteristics to the first nearby VIX futures, i.e. positive skewness, excess kurtosis, autocorrelation close to 1 and a unit root. As expected, the first nearby contract is more liquid (average daily volume of 18,858) than the second nearby contract (average daily volume of 13,006). Finally, we observe that signed order flow is on average positive in both future contracts. This means that investors in VIX futures mostly take long positions, and is in line with the common contango shape in the term structure of VIX futures.

Insert Table 1 Here

In the lower part of Table 1, we report summary statistics over two sub-periods, before and after the introduction of the VIX ETPs. We note stark differences between the two periods. We observe that the first period was primarily one where volatility increased (hence the positive return on the VIX futures), while the second period was a period when volatility decreased.

It is interesting to note substantial differences in the trading behavior of the VIX futures before and after the introduction of the VIX ETPs. Prior to the introduction of the VIX ETPs trading volume was, on average, about 1,580 and 800 contracts per day for the first and second nearby contracts, respectively. After the introduction of the VIX ETPs, the trading increased to about 28,000 and 19,300 contracts per day for the first and second nearby contracts, respectively. Even more interesting is the difference in signed order flow in the VIX futures over the two periods. In the period before the introduction of the VIX ETPs, signed order flow was close to zero (-76.81 and 37.05 in the first and second nearby contracts, respectively), but, one average, positive after the introduction of the VIX ETPs (1,123 and 674 in the first and second nearby contracts, respectively).

Lastly, we observe that the percentage spread has declined after the introduction of the VIX ETPs which could be attributed to the increased liquidity in the VIX futures.

5. Empirical Findings

5.1. Model Estimates

We estimate the model described in Section 2 for both the first and second nearby futures contracts. We estimate the model for each day.[6] However, we require a day to have at least 75 transactions to ensure that the parameter estimates for that day are meaningful.[7] To compute the surprise in order flow, $\hat{O}_t$, we estimate an autoregressive model, where the optimal lag length for each day is selected based on the Akaike Information Criterion (AIC).

In Table 2, we report the parameter estimates for the model. More specifically, we report the daily average parameter estimates as well as the Newey-West corrected t-statistic in parentheses that are computed based on the daily parameter estimates. Panel A shows the results for the first nearby contract, with the top part of Panel A showing the estimates for the permanent price process. The impact of trade on the efficient price is positive and highly significant at a value of 0.21 bps per contract, thus showing that trade in the VIX futures is to some degree informed. However, when we consider the period before and after the introduction of the VIX ETPs, we observe that the impact of

[6]The regular trading hours in VIX Futures are between 9:30 a.m. and 4:15 p.m. Eastern Standard Time (EST) so we use the information during these regular trading hours, ignoring the extended trading hours.

[7]The minimum number of transactions per day is somehow arbitrary but the results are qualitative similar for another values such as 100 and 225 transactions. Results are available from the authors.

trade on the efficient price has changed considerably. During the first phase, the information content of trades in the VIX futures is 0.44 bps per contract. This decreases to 0.13 bps per contract during the time period when VIX ETPs were introduced. This drop in the informativeness of trade suggests that in the second period more trade in the VIX futures are driven by liquidity than by information.

Insert Table 2 Here

Given the definition of the efficient price process, we can perform a decomposition of the variance of this process. Specifically, given Equation (2), we can define the variance of the change in the efficient price as

$$Var(\Delta m_t) = \lambda^2 Var(\hat{O}_t) + Var(\varepsilon_t) \ . \tag{4}$$

We report the separate components of Equation (4) in the Table 2. In addition, we report the percentage of the variance of the efficient price that is trade-induced, or stated differently, that is due to private information. This measure is similar to Hasbrouck's (1991) measure of trade informativeness, but is computed on a trade-by-trade basis, instead of over a calendar time interval.

When we first consider $Var(\varepsilon_t)$, the variance of trade-unrelated news shocks to the efficient price, we observe that it has declined substantially over the two time periods. This is expected, because the trading frequency has increased in the VIX futures over the sample period, and $Var(\varepsilon_t)$ measures the amount of public information arrival over the interval between trades. Likewise, when we consider the variance of the efficient price process due to trade, $\lambda^2 Var(\hat{O}_t)$, we observe that this has declined over the two subsamples. However, both measures are a function of liquidity in the market, and we would expect that both measures to decline as trading activity increases. So in order to carry out a fair comparison between subperiods, we consider the relative contributions to the variance of changes in the efficient price. We observe that over the full sample period 5.49% of this variance is trade related. Thus information coming from trade contributes only 5.49% to the variance of the efficient price changes. Over the two different sample periods, we observe that the contribution of trade to the variance of the efficient price has declined from 8.18% to 4.49%, showing that on a relative basis, trading activity in the VIX futures has become less informative.

When we consider the impact of trades on the pricing error, θ, we observe that this effect is, on average, -0.37 bps per contract. The negative sign for this parameter is in line with Brogaard et al. (2014), and suggests that trade is generally in the direction against the pricing error. Hence, our result points out to the fact that traders recognize when a pricing error occurs and trade against it. When we consider the two different phases, it can be observed that the parameter during the first phase is -0.72 bps per contract, but drops considerably during the second phase to -0.25 bps per contract. This decline in the trading activity against the pricing error over the last period may be a consequence of the ETPs trading for liquidity purposes.

We next present the results for φ, the parameter that captures the persistence in the pricing error. Over the full sample period, φ is equal to 0.36, suggesting that there is persistence in the pricing error. When we consider the two different phases of the VIX futures, we note that the persistence in the pricing error has been increasing from 0.22 in the first phase of the VIX futures to 0.42 in the second phase. This increase suggests that pricing error persist more in the period after the VIX ETPs were introduced. Combining this persistence in pricing error with the previous result on the impact of order flow on the mispricing, we can conclude that in the last phase trade is less against the mispricing and that mispricing seems to persist longer.

Similar to a variance decomposition of the efficient price, we can also perform a variance decomposition of the transitory part of the price process. Since the transitory part is already stationary, we can compute the variance of the transitory part directly from Equation (3), i.e.

$$Var(s_t) = \varphi^2 Var(s_{t-1}) + \theta^2 Var(O_t) + Var(\eta_t)\,. \tag{5}$$

Equation (5) shows that the variance of the transitory process has three components, a component due to the persistence in the pricing error, a part due to trade in the VIX futures and a part due to random noise.[8] Rearranging Equation (5) and using the fact that $Var(s_t) = Var(s_{t-1})$ we obtain

[8]The random noise in the transitory process could be due to e.g. price discreteness.

$$Var(s_t) = \frac{\theta^2 Var(O_t) + Var(\eta_t)}{(1-\varphi^2)}. \qquad (6)$$

As pricing errors can be both induced by trade and the persistence that trade shocks will have on the pricing error, we are interested in determining the contribution of both persistence and trade to the total variance of the pricing error. The percentage contribution of persistence is simply given as φ^2, whereas the contribution of trade is given as $\frac{\theta^2 Var(O_t)}{Var(s_t)}$.

In the next rows of Table 2, we first report the variance of the transitory price process, *Var(*s_t*)*. As we can see, this variance has decreased substantially over the two subperiods. Again this decline is most likely due to the increase in trading activity. When we look at the percentage contribution to this variance of the persistence term, φ^2, we observe that this percentage has increased over the two periods from 15.68% to 21.90%, suggesting that more of this variance is coming from persistence. However, the contribution of trade to this variance has decreased from 34.48% to 16.35%.

A final measure that is of interest is the ratio that looks at the contribution of the variance of the efficient price changes to the total price changes. Specifically, in our case, this is defined as the decomposition of intraday returns, i.e.

$$Var(\Delta p_t) = Var(\Delta m_t) + Var(\Delta s_t), \qquad (7)$$

where $Var(\Delta m_t)$ is given in Equation (4), and $Var(\Delta s_t)$ is given as

$$Var(\Delta s_t) = \varphi^2 Var(\Delta s_{t-1}) + \theta^2 Var(\Delta O_t) + Var(\Delta \eta_t) \ . \tag{8}$$

Since $Var(\Delta s_t) = Var(\Delta s_{t-1})$, $Var(\Delta \eta_t) = 2Var(\eta_t)$ and $Var(\Delta O_t) = 2(1-\rho)Var(O_t)$, where ρ is the first-order autocorrelation in order flow, we can rewrite and rearrange Equation (8) as

$$Var(\Delta s_t) = \frac{2\left[\theta^2(1-\rho)Var(O_t) + Var(\eta_t)\right]}{(1-\varphi^2)} . \tag{9}$$

We can now determine the contribution of the change in the efficient price and change in the transitory component to the variance of price changes.

In the last row of Panel A, we report the percentage of the variance of the price change that is due to the variance in the efficient price, i.e. $\frac{Var(\Delta m_t)}{Var(\Delta p_t)}$. Over the full sample period, we see that this percentage is about 38%, but is higher in the first part of the sample at 55% and drops to 32% in the second part of the sample. This decline suggests that over time the noise component of price changes has increased.

The decrease in the informativeness of price changes over the two sub-periods is worth further investigation. In Figure 2, we plot the evolution of the percentage of the variance of the price change that is due to the variance in the efficient price over time, the evolution of monthly averages. From the start of the sample up to the introduction of the VIX ETPs, we observe that the informativeness of price changes was generally increasing, reaching a maximum of nearly 73% at the time when the VIX ETPs were introduced. By contrast, since the introduction of the VIX ETPs, we generally observe a downward trend in this ratio, reaching a low point at the end of the sample where the contribution is only about 7%. This picture may suggest that the introduction of VIX ETPs had an impact on the informativeness of price changes. We do observe another noteworthy feature in Figure 2, the informativeness of the price changes seems to increase at times when the VIX increases. We will further investigate the relation between the informativeness of the price process, trading activity and market conditions in the following sections.

Insert Figure 2 Here

In Panel B, we report the results for the second nearby futures contract. The results for the second-nearby contract are broadly in line with those presented in Panel A. We note that the information content of trades declines in the second period, and the percentage contribution of trades to the variance of the efficient price changes declines over time as well. This finding again implies that trades have become less informative. As for the first-nearby contract, we observe once more that the order flow has a negative impact on the pricing error, and this negative impact reduces when going from the first to the second sub-sample period. Similarly, persistence in order flow increases.

5.2 Intraday Variation

The next issue we aim to assess is whether there is time variation within the day in the coefficients that drive the price process for the VIX futures. We are particularly interested in determining whether the price process is different during the opening and the closing periods of the market. The opening period is of particular interest as this is the point of time when the market needs to incorporate the information that has been accumulated overnight. This period is also of interest as many studies have documented that it is the time when most private information are revealed (see e.g. Madhavan et al., 1997). The closing period is of interest as many VIX ETPs need to rebalance their positions in line with their VIX mandate, and in order to get the most accurate hedge possible, many VIX ETPs tend to rebalance near the close of the trading day. We thus extend the state space model to the following equation,

$$\begin{cases} p_t = m_t + s_t \\ m_t = m_{t-1} + (\lambda_1 D_{1t} + \lambda_2 D_{2t} + \lambda_3 D_{3t})\hat{O}_t + \varepsilon_t \\ s_t = (\varphi_1 D_{1t} + \varphi_2 D_{2t} + \varphi_3 D_{3t}) s_{t-1} + (\theta_1 D_{1t} + \theta_2 D_{2t} + \theta_3 D_{3t}) O_t + \eta_t \end{cases}, \tag{10}$$

where D_{1t} is a dummy variable that is equal to one during the first 60 minutes of the trading day and zero otherwise, D_{2t} is a dummy variable that is equal to one during the middle of the trading day and zero otherwise, and D_{3t} is a dummy variable that is equal to one during the last 90 minutes of the trading day and zero otherwise. The parameters λ_1, λ_2, and λ_3 capture the price impact of trades during the open, middle and close, respectively; φ_1, φ_2, and φ_3 capture the persistence in the pricing error during the three periods and θ_1, θ_2, and θ_3 capture the impact of trade on the pricing error.

We report the results in Table 3, where Panel A presents the results for the first nearby contract and Panel B for the second nearby contract. For the first nearby contract, we observe that price impact of trades is highest in the first 60 minutes, λ_1. However, instead of a gradual decline over the day, as documented in other market microstructure studies (see e.g. Madhavan et al., 1997), we observe an increase in the price impact of trades towards the end of the day. This pattern is very pronounced in the first period but is not present in the second period which is broadly constant after the first 60 minutes of the trading day. We do note that the price impact of trades declines substantially for all parts of the day when going for the first to the second sub-period. The contribution of the trade-induced variance to the total variance of the efficient price remains rather stable across the day, but we do observe that the overall contribution declines in the second sub-period after the introduction of the VIX ETPs.

Insert Table 3 Here

When we focus on the transitory part for the intraday period, we note that in the first sub-period this impact display an inverse U-shaped pattern, with strong corrections of the pricing errors at the start and end of the trading day. However, in the second part of the sample, we observe that firstly the impact of trade on the pricing error becomes less negative and secondly it becomes less negative throughout the trading day. These observations suggest that as we move towards the close of the trading day, there is less correction of the pricing error. This may again be a consequence of the trading of ETPs, which is mostly focused towards the end of the trading day. Finally, when we consider the persistence in the transitory component, we observe that overall persistence increases when moving from the first sub-period to the second one. Interestingly, we also observe that this persistence is rather constant during the day in the first sub-period (with a slight inverse U-shape), but is increasing (in particular in the closing period) in the second sub-period.

Similar to the daily estimates, we can decompose the variance of the price changes into the variance of efficient price change and the variance of the pricing error for the different parts of the day. The last rows of Panel A in Table 3, report these percentages. Overall, we observe that the informativeness of the price changes declines slightly over the course of the trading day going from about 40% during the first 60 minutes of the trading day to 38% at the end of the trading day. When looking at the two subsamples, we observe that while this decline is present in the second subsample (from 35% to 32%); it is broadly constant in the first subsample (around 61%). This result may suggest that the intraday pattern may also be affected by the hedging activities of the VIX ETPs.

The results for the second-nearby contract, reported in Panel B of Table 3, are broadly in line with those for the first nearby contract.

5.3 Properties of the VIX futures price process on high versus low volatility days

In this section, we examine whether the properties of the price process are different on days with high versus low market volatility. These days are of particular interest in the second part of our sample, where VIX ETPs are traded actively. When implied volatility is high, there is generally a high selling activity in VIX ETPs that are long in VIX, as these investors are cashing in on the profits they made in their positions. Hence, on days with high levels of the VIX, we expect that the trading pressure of the VIX ETPs on the VIX futures is high. We thus split our sample in high versus low VIX days and examine the properties on those different days.

In Table 4, we show the results when we split the sample into high and low volatility days where high volatility days are those where the VIX is one standard deviation higher than the full sample mean (i.e., VIX > 31.46), and low volatility days are the other days.

Insert Table 4 Here

Table 4 shows that the properties of the price process are considerably different on high versus low volatility days. First, we observe that the price impact of trades, λ, is much higher on high volatility days than on low volatility days. However, we also observe that the variance of non-trade related information, $Var(\varepsilon_t)$, is much higher on high volatility days. This can be expected as there may be a higher arrival rate of public news on such days. When we consider the contribution of trade related information to the variance of the efficient price process, $\frac{\lambda^2 Var(\hat{O}_t)}{Var(\Delta m_t)}$, we observe, according to the t-test, there is no significant difference between high and low volatility days. This is a consequence of both trade being more informative, but also more public news arrival.

When we turn to the properties of the process for the pricing error, we observe that the correction in the pricing error, θ, is much stronger on high volatility days than on low volatility days. Similarly, the persistence in the pricing error is much lower on high volatility days. Combining the facts that there is a higher price impact of trades and greater arrival of public information with the observation that the pricing error corrects more quickly and has less persistence, leads to the observation that the changes in the price of the VIX futures are more driven by the efficient price process than by noise. The variance ratio of efficient price changes to total price change is about 63% on high volatility days versus 34% on low volatility days.

6. Conclusion

In this paper, we examine the market microstructure properties of VIX futures, before and after the introduction of the VIX ETPs. We document that the introduction had a pronounced impact on the intraday price dynamics of VIX futures, where trades have become less informative, and where pricing errors are more persistent after the introduction of the VIX ETPs. In addition, we document that the price process of the VIX futures has become noisier over time. These findings suggest that the introduction of the VIX ETPs had a pronounced effect on the intraday properties and dynamics of the VIX futures, and shed light on the efficiency of the VIX futures.

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Table 1: Summary Statistics

	Panel A: Full sample									
	Front end VIX Futures					*Second end VIX Futures*				
	Price	Returns (annual)	Volume (x 1,000)	Signed Order Flow (x 100)	%Spread	Price	Returns (annual)	Volume (x1,000)	Signed Order Flow (x100)	%Spread
Mean	21.62	1.51%	18.86	7.12	0.35%	22.38	1.58%	1.30	4.56	0.37%
Std	9.42	81.83%	25.13	26.01	0.18%	8.39	56.53%	1.78	23.12	0.24%
Max	67.95	27.33%	207.49	283.78	2.14%	59.74	17.31%	144.08	209.18	5.73%
Min	10.26	-29.29%	0.003	-144.36	0.14%	11.69	-17.42%	2.00	-116.50	0.15%
Skewness	1.81	0.61	2.19	1.45	3.75	1.42	0.51	2.12	2.08	8.55
Kurtosis	6.93	6.36	9.93	14.79	24.65	5.40	5.86	9.05	14.01	144.75
JB test	2,552***	1,139***	5,991***	13130***	46,813***	1,231***	822***	4,860***	12361***	1,821,025***
ρ(1)	0.99***	-0.07***	0.89***	0.14***	0.75***	0.99***	-0.06***	0.88***	0.30***	0.61***
ADF	-1.00	-36.14***	-2.61***	-7.27***	-2.65***	-0.75	-34.88***	-3.29***	-7.45***	-2.92***

	Panel B: Before introduction of VIX ETPs									
	Front end VIX Futures					*Second end VIX Futures*				
	Price	Returns (annual)	Volume (x 1,000)	Signed Order Flow (x 100)	% Spread	Price	Returns (annual)	Volume (x 1,000)	Signed Order Flow (x 100)	% Spread
Mean	21.81	43.08%	1.58	-0.77	0.47%	21.65	39.90%	0.80	0.37	0.54%
Std	12.18	81.37%	1.56	6.21	0.26%	10.41	53.53%	0.94	4.74	0.35%
Max	67.95	25.32%	11.25	51.01	2.14%	59.74	14.22%	11.34	39.45	5.73%
Min	10.26	-29.29%	0.003	-41.42	0.17%	11.69	-15.37%	0.002	-21.99	0.18%
Skewness	1.84	27.71%	2.10	-1.28	2.33	1.72	0.32	3.55	1.64	6.71
Kurtosis	5.94	7.01	9.81	19.83	11.38	5.64	5.58	28.19	17.92	81.46
JB test	678***	501***	1958***	8854***	2818***	575***	216***	20891***	7120***	194313***
ρ(1)	0.99***	-0.05	0.63***	0.10**	0.65***	0.99***	-0.06*	0.41***	0.13***	0.46***
ADF	0.12	-21.21***	-2.67***	-7.26***	-1.70*	0.41	-20.36***	-3.51***	-7.02***	-2.07**

	Panel C: After introduction of VIX ETPs									
	Front end VIX Futures						*Second end VIX Futures*			
	Price	Returns (annual)	Volume (x 1,000)	Signed Order Flow (x 100)	% Spread	Price	Returns (annual)	Volume (x 1,000)	Signed Order Flow (x 100)	% Spread
Mean	21.52	-20.15%	27.86	11.23	0.29%	22.76	-18.34%	19.35	6.74	0.28%
Std	7.60	82.06%	26.88	30.99	0.06%	7.09	58.01%	19.02	28.05	0.05%
Max	49.05	27.33%	207.49	5.70	0.44%	46.93	17.31%	144.08	0.87	0.49%
Min	11.78	-23.24%	0.370	-144.36	0.14%	12.73	-17.42%	0.169	-116.50	0.15%
Skewness	1.25	0.78	1.81	0.93	-0.05	0.92	0.60	1.73	1.54	-0.02
Kurtosis	4.18	6.07	8.33	10.54	2.57	3.39	5.96	7.40	9.31	2.86
JB test	447***	695***	2438***	3537***	11***	209***	597***	1837***	2891***	1
ρ(1)	0.98***	-0.09**	0.85***	0.09**	0.95***	0.99***	-0.06**	0.85***	0.29***	0.91***
ADF	-1.87*	-29.19***	-2.11**	-5.82***	-0.49	-1.80*	-28.20***	-2.66***	-5.99***	-0.26

Note: This table reports summary statistics for the first and second nearby VIX futures contracts. We present summary statistics for the full sample (from 24 February 2006 to 02 September 2014) and the period before and after the introduction of the VIX ETPs on 29 January 2009.

Table 2. Parameter Estimates for the VIX futures price process

		Panel A: First-nearby Contract		
Permanent Price Process				
	Units	Full sample	Before	After
λ	bps/contract	0.2145	0.4387	0.1307
		(8.00)	(12.58)	(4.12)
$Var(\varepsilon_t)$	bps^2	128.8876	326.6951	54.8684
		(10.57)	(10.81)	(15.09)
$Var(\hat{O}_t)$	Contracts^2	1313.7764	1137.2927	1379.8163
		(10.11)	(4.98)	(8.98)
$\lambda^2 Var(\hat{O}_t)$	(bps/contract)^2	10.7867	29.4320	3.8097
		(7.47)	(7.13)	(6.32)
$\dfrac{\lambda^2 Var(\hat{O}_t)}{Var(\Delta m_t)}$	%	5.49%	8.18%	4.49%
		(16.84)	(12.48)	(13.20)
Transitory Price Process				
θ	bps/contract	-0.3746	-0.7191	-0.2457
		(-11.51)	(-14.39)	(-6.91)
φ		0.3607	0.2153	0.4151
		(33.76)	(15.50)	(36.67)
$Var(s_t)$	bps^2	116.4693	245.5907	68.1523
		(10.82)	(7.85)	(28.24)
φ^2	%	20.21%	15.68%	21.90%
		(29.62)	(15.58)	(26.74)
$\dfrac{\theta^2 Var(O_t)}{Var(s_t)}$	%	21.29%	34.48%	16.35%
		(20.27)	(21.83)	(15.07)
$\dfrac{Var(\Delta m_t)}{Var(\Delta p_t)}$	%	37.92%	54.88%	31.57%
		(28.66)	(40.70)	(21.50)

Panel B: Second-nearby Contract				
Permanent Price Process				
	Units	Full sample	Before	After
λ	bps/contract	0.2495	0.7170	0.1162
		(8.19)	(12.24)	(4.35)
$Var(\varepsilon_t)$	bps^2	114.9603	351.7368	47.4545
		(9.68)	(10.84)	(12.94)
$Var(\hat{O}_t)$	$Contracts^2$	853.2193	651.3368	910.7766
		(12.96)	(3.72)	(13.60)
$\lambda^2 Var(\hat{O}_t)$	$(bps/contract)^2$	12.4973	41.8452	4.1302
		(7.72)	(9.25)	(5.06)
$\frac{\lambda^2 Var(\hat{O}_t)}{Var(\Delta m_t)}$	%	5.49%	10.92%	3.94%
		(14.41)	(12.47)	(11.90)
Transitory Price Process				
θ	bps/contract	-0.4059	-1.0712	-0.2162
		(-10.55)	(-14.27)	(-6.96)
φ		0.4023	0.2735	0.4390
		(36.87)	(14.81)	(38.00)
$Var(s_t)$	bps^2	119.9155	321.6675	62.3954
		(9.65)	(7.41)	(26.41)
φ^2	%	23.88%	20.13%	24.95%
		(30.51)	(17.70)	(26.62)
$\frac{\theta^2 Var(O_t)}{Var(s_t)}$	%	18.76%	37.03%	13.55%
		(16.16)	(19.56)	(12.39)
$\frac{Var(\Delta m_t)}{Var(\Delta p_t)}$	%	34.75%	50.90%	30.14%
		(26.56)	(30.77)	(21.22)

Note: This table reports results for the parameter estimates of the State Space Model developed in Section 2. The model is estimated for every day and we report the average coefficient along with the Newey-West adjusted t-statistic in parentheses. We report results over the full sample and for the period before and after the introduction of the VIX ETPs.

Table 3. Intraday variation in the properties of the VIX futures price process

Panel A: First-nearby contract				
Permanent Price Process				
	Units	Full sample	Before	After
λ_1	bps/contract	0.3264	0.7571	0.2166
		(8.04)	(10.64)	(5.14)
λ_2	bps/contract	0.2547	0.5500	0.1794
		(7.30)	(11.93)	(4.55)
λ_3	bps/contract	0.2915	0.7641	0.1710
		(7.45)	(10.61)	(4.36)
$\frac{\lambda_1^2 Var(\hat{O}_t)}{Var(\Delta m_t)}$	%	2.74%	3.99%	2.42%
		(17.79)	(10.53)	(15.59)
$\frac{\lambda_2^2 Var(\hat{O}_t)}{Var(\Delta m_t)}$	%	3.57%	5.20%	3.15%
		(17.89)	(12.39)	(14.69)
$\frac{\lambda_3^2 Var(\hat{O}_t)}{Var(\Delta m_t)}$	%	2.90%	3.87%	2.65%
		(13.89)	(10.36)	(11.04)
Transitory Price Process				
θ_1	bps/contract	-0.6220	-1.2698	-0.4569
		(-12.68)	(-14.49)	(-9.57)
θ_2	bps/contract	-0.4626	-0.8625	-0.3606
		(-11.28)	(-13.76)	(-8.03)
θ_3	bps/contract	-0.4697	-1.2424	-0.2727
		(-9.21)	(-12.61)	(-5.89)
φ_1		0.3335	0.2239	0.3615
		(28.92)	(10.07)	(29.15)
φ_2		0.3500	0.2471	0.3762
		(27.78)	(12.24)	(26.30)
φ_3		0.4199	0.1837	0.4801
		(26.05)	(8.70)	(29.21)
$\frac{Var_1(\Delta m_t)}{Var_1(\Delta p_t)}$	%	40.46%	61.77%	35.03%
		(27.10)	(42.67)	(22.30)
$\frac{Var_2(\Delta m_t)}{Var_2(\Delta p_t)}$	%	39.39%	59.42%	34.29%
		(26.35)	(33.64)	(21.61)
$\frac{Var_3(\Delta m_t)}{Var_3(\Delta p_t)}$	%	38.24%	61.83%	32.22%
		(24.13)	(39.17)	(19.64)

Panel B: Second-nearby contract				
Permanent Price Process				
	Units	Full sample	Before	After
λ_1	bps/contract	0.2145	0.8434	0.1372
		(6.00)	(4.60)	(4.89)
λ_2	bps/contract	0.1698	0.5926	0.1179
		(7.06)	(8.06)	(5.57)
λ_3	bps/contract	0.1984	0.8415	0.1194
		(6.02)	(7.12)	(4.18)
$\frac{\lambda_1^2 Var(\hat{O}_t)}{Var(\Delta m_t)}$	%	2.40%	4.96%	2.09%
		(13.18)	(7.65)	(11.99)
$\frac{\lambda_2^2 Var(\hat{O}_t)}{Var(\Delta m_t)}$	%	2.93%	6.56%	2.48%
		(12.78)	(8.15)	(11.77)
$\frac{\lambda_3^2 Var(\hat{O}_t)}{Var(\Delta m_t)}$	%	3.12%	5.71%	2.80%
		(10.47)	(6.23)	(9.28)
Transitory Price Process				
θ_1	bps/contract	-0.4719	-1.3724	-0.3612
		(-11.31)	(-7.62)	(-11.72)
θ_2	bps/contract	-0.3503	-0.9628	-0.2751
		(-11.61)	(-8.92)	(-11.29)
θ_3	bps/contract	-0.3397	-1.4434	-0.2040
		(-7.38)	(-9.95)	(-5.78)
φ_1		0.3360	0.2114	0.3513
		(29.36)	(6.72)	(29.81)
φ_2		0.3813	0.2969	0.3917
		(28.54)	(7.51)	(27.97)
φ_3		0.4812	0.2480	0.5099
		(31.60)	(7.18)	(33.81)
$\frac{Var(\Delta m_t)}{Var(\Delta p_t)}$ (open)	%	35.81%	57.45%	33.15%
		(24.20)	(24.82)	(22.11)
$\frac{Var(\Delta m_t)}{Var(\Delta p_t)}$ (mid)	%	34.50%	52.48%	32.29%
		(23.16)	(21.07)	(20.81)
$\frac{Var(\Delta m_t)}{Var(\Delta p_t)}$ (close)	%	32.17%	54.09%	29.48%
		(21.08)	(20.99)	(19.06)

Note: This table reports results for the parameter estimates of the intraday State Space Model developed as in Equation (10). The model is estimated for every day and we report the average coefficient along with the Newey-West adjusted t-statistic in parentheses. We report results over the full sample and for the period before and after the introduction of the VIX ETPs. Parameters with a subscript 1, refer to the estimates for the first 60 minutes of the trading day. Parameters with a subscript 2, refer to the estimates for the middle of the trading day. Parameters with a subscript 3, refer to the estimates for the last 90 minutes of the trading day.

Table 4. Properties of the VIX futures on High versus Low Volatility Days

	λ	$Var(\varepsilon_t)$	$Var(\hat{O}_t)$	$\lambda^2 Var(\hat{O}_t)$	$\frac{\lambda^2 Var(\hat{O}_t)}{Var(\Delta m_t)}$	θ	φ	$Var(\eta_t)$	$Var(s_t)$	$\frac{Var(\Delta m_t)}{Var(\Delta p_t)}$
					Front end VIX Futures					
					VIX>31.46					
Mean	0.7652	226.8880	400.3603	18.1375	0.0605	-1.0710	0.2234	37.1592	83.5415	0.6311
t-stat	(8.50)	(10.30)	(1.65)	(7.33)	(10.19)	(-11.15)	(12.86)	(4.56)	(6.79)	(45.43)
					VIX<31.46					
Mean	0.1318	114.1525	1451.1159	9.6815	0.0541	-0.2699	0.3813	67.5960	121.4203	0.3413
t-stat	(13.67)	(19.23)	(11.14)	(7.84)	(19.29)	(-19.82)	(42.05)	(13.57)	(15.54)	(31.89)
T-test (diff.)	17.84	6.89	-3.06	2.69	1.02	-18.71	-8.88	-2.33	-1.98	18.61
Wilcoxon	7.45	13.40	-17.73	8.63	2.76	-12.21	-9.83	-12.19	-7.76	16.55
					Second end VIX Futures					
					VIX>31.46					
Mean	0.7935	282.1977	216.2881	27.5196	0.0636	-1.0585	0.2481	45.3590	118.4701	0.6272
t-stat	(9.04)	(7.87)	(2.84)	(5.44)	(9.32)	(-11.74)	(12.89)	(4.16)	(5.15)	(36.61)
					VIX<31.46					
Mean	0.1651	89.0337	951.9620	10.1685	0.0535	-0.3047	0.4262	61.1984	120.1396	0.3041
t-stat	(10.70)	(13.79)	(16.43)	(9.24)	(17.43)	(-13.78)	(46.22)	(7.93)	(11.61)	(28.56)
T-test (diff.)	13.75	12.73	-5.04	5.59	1.43	-13.45	-9.51	-0.79	-0.06	20.76
Wilcoxon	8.00	15.88	-16.49	8.24	1.53	-12.30	-9.44	-10.34	-5.17	17.39

Note: This table reports results for the model, where days are separated based on the level of the VIX. We split days into high volatility days (VIX exceeds its mean plus one standard deviation), and normal days (other days). We report the average parameter estimates along with Newey-West adjusted t-statistics in parentheses.

Figure 1. Evolution of VIX and VIX futures

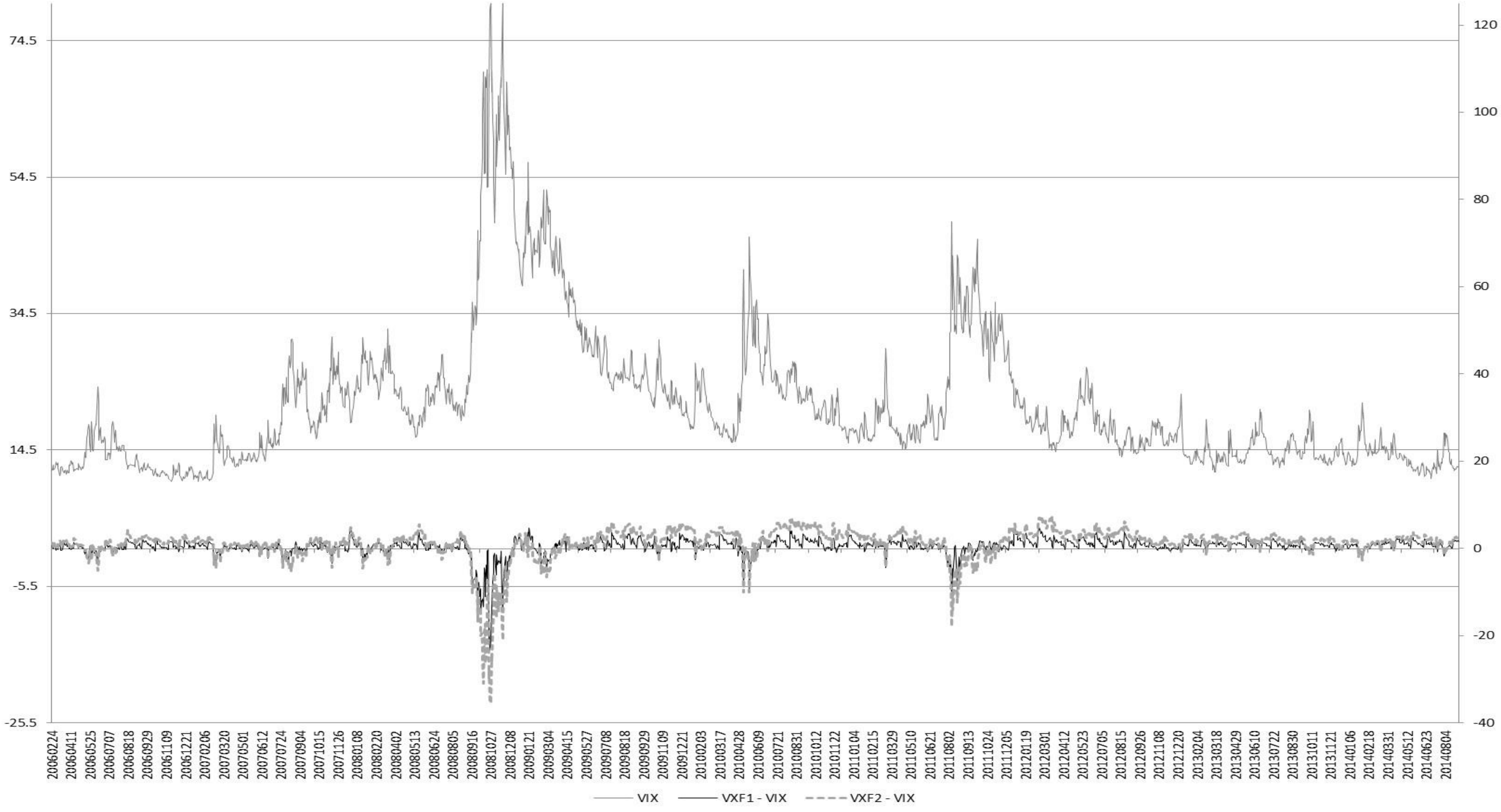

Figure 2. Time Variation in $\frac{Var(\Delta m_t)}{Var(\Delta p_t)}$