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Essays on the Term Structure of Volatility and Option Returns

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ESSAYS ON THE TERM STRUCTURE OF VOLATILITY AND OPTION RETURNS

A Dissertation Presented

by

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ABSTRACT

ESSAYS ON THE TERM STRUCTURE

OF VOLATILITY AND OPTION RETURNS

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The first essay studies the dynamics of equity option implied volatility and shows that they depend both upon the option's time to maturity (horizon) and slope of the implied volatility term structure for the underlying asset (term structure). We propose a simple, illustrative framework which intuitively captures these dynamics. Guided by our framework, we examine a number of volatility trading strategies across horizon, and the extent to which profitability of trading strategies is due to an interaction between term structure and realized volatility. While profitable trading strategies based upon term structure exist for both long and short horizon options, this interaction requires that positions in long horizon options be very different than those required for short horizon options.

Equity option returns depend upon both term structure and horizon, but for index options, implied volatility term structure slope negatively predicts returns. While the carry trade has been applied profitably across asset classes and to index volatility, given this difference in index and equity implied volatility dynamics, I examine the carry trade in the equity volatility market in the second essay. I show that the carry trade in equity volatility produces significant returns, and unlike the returns to carry in other asset classes, is not exposed to liquidity or volatility

risks and negatively loads on market risk. A long volatility carry portfolio, after transactions costs, remains significantly profitable and negatively loads on market risks, challenging traditional asset pricing theories.

Overwriting an index position with call options creates a portfolio with fixed exposures to market and volatility risk premia. I allow for time-varying allocations to volatility and the market by conditioning on the slope of the implied volatility term structure. I show that a three asset portfolio holding a VIX futures position, the S&P 500 Index and cash triples the returns of the index and more than doubles the risk-adjusted returns of the covered call while maintaining a return volatility roughly equal to that of the S&P 500 Index.

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CHAPTER 1

UNDERSTANDING AND TRADING THE TERM STRUCTURE OF VOLATILITY

1.1 Introduction

We study the behavior of volatility embedded in equity option prices across different maturities. Our focus is on how the dynamics of option implied volatility is related to the term structure of volatility in the cross-section of equity options. We show that volatility dynamics depend both upon time to maturity (horizon) of options and slope of the implied volatility term structure for the underlying asset (term structure). Furthermore, the dynamics crucially depend upon an interaction between horizon and term structure: for stocks with similar term structure, dynamics are strongly dependent upon horizon. For options with a given horizon, the dynamics of volatility depend upon term structure. In addition, we show that the relationship between implied volatility and *realized* volatility of the underlying stock depends upon horizon and term structure. This relationship between realized and implied volatility has implications for the volatility risk premia of individual stocks.

We contribute to a rapidly growing literature seeking to understand the term structure of risk prices. Van Binsbergen, Brandt, and Koijen (2012) and Van Binsbergen, Hueskes, Koijen, and Vrugt (2013) study the prices of market risk as measured by the Sharpe Ratios of claims to dividends on the market index at different horizons. These papers sparked a large interest in the idea that even though equity is a claim on cash flows over an infinite horizon, the risks associated with different horizons could be priced differently.[1] Shortly thereafter, Dew-Becker, Giglio, Le, and Rodriguez (2015), Aıt-Sahalia, Karaman, and Mancini (2014) and Johnson (2016) extended the idea of studying the term structure of prices of risk, examining market volatility prices at different horizons.[2] These recent papers all document a consistent finding across asset classes: for *unconditional* prices of risk associated with market expected returns and volatility, the longer the horizon over which the risk is measured, the smaller the magnitude of that risk's price. The consistency of findings across asset classes and types of risk (market and volatility) suggests something fundamental about investors' risk preferences over varying time horizons. However, most theoretical asset pricing models fail to explain these findings.[3]

While the majority of volatility and equity term structure papers focus on the unconditional properties of risk prices, little is known about the dynamics of implied volatility and its term structure. A small number of papers have examined trading strategies based upon the slope of the volatility term structure: Johnson (2016) shows that the slope of the VIX term structure predicts future returns to variance assets. Specifically, he finds that slope negatively predicts returns: An upward-sloping curve results in negative returns on variance assets; a downward-sloping curve produces relatively higher, and in some cases positive, returns.[4] Vasquez (2015) and Jones and Wang (2012) both examine the cross-sectional returns of short-term equity options straddles, conditioned on the slopes of each stock's volatility curve. They independently find that variations in slope predict returns for short maturity straddles. Interestingly, their findings suggest the relation between term structure and future straddle returns of individual options has the opposite sign as the relation shown by Johnson (2016) who uses index

[1]See Rietz (1988), Campbell and Cochrane (1999), Croce, Lettau, and Ludvigson (2008), Bansal and Yaron (2004), and Barro (2006). See Han, Subrahmanyam, and Zhou (2015) for an examination of the term structure of credit risk premia.

[2]See also Cheng (2016).

[3]Barro (2006), Rietz (1988), and Gabaix (2008) are consistent with these findings.

[4]See also Simon and Campasano (2014).

options: In the cross-section of equity options, term structure *positively* predicts returns of short-maturity straddles. An upward-sloping curve results in relatively *high* returns, and an inverted curve produces *low* returns. This difference between conditional returns to index and equity option straddles highlights the importance of separately studying equity and index options.

In order to examine the relation between the dynamics of volatility and term structure slope, we require a large cross-section of assets. For this reason, we use the cross-section of options on individual names in our study. While not as liquid as index options in general, the market for individual options is large and relatively liquid. The large cross-section provides a nice setting for our study because it allows us to examine the joint dynamics of short and long term volatility *conditional* on a firm's term structure slope. At any point in time, we can examine the dynamics among firms with a wide array of term structure slopes. This helps give us a better sense of how term structure affects implied volatility dynamics.

By examining the movement of equity option prices using both at the money (ATM) implied volatility and ATM straddle returns with one through six month maturities, we document the term structure behavior. We find that the term structure inverts (becomes downward sloping) due largely to an increase in one month implied volatility as opposed to an increase in volatility of the underlying asset. Thus we find a strong relationship between slope of volatility term structure and volatility risk premia in short maturity options. Accordingly, we find that as the term structure inverts, the impact of realized volatility on the slope diminishes. Whereas the risk premia in one month options increase as term structure becomes inverted, the volatility risk premium for longer maturity options reverses as the curve steepens: we find a *decrease* in the risk premium for 6 month volatility as the term structure slope decreases (becomes more inverted). Surprisingly, the average volatility risk premia for 6 month options becomes negative for equities whose term structure curve has the lowest slope (is more inverted).

We propose a simple framework for understanding the dynamics which encapsulate our empirical findings. Based upon these insights, we then examine the returns to trading strategies using ATM straddles with maturities of one to six months. Consistent with prior research, we find economically and statistically significant negative returns, a loss of 11.85% per month, for short-maturity straddles when the slope is most negative. As the slope increases, we find the returns of the one month straddles monotonically increase. When examining the returns of two month straddles, the pattern, although weaker, persists. This pattern disappears in the three and four month maturity options. As we look at longer maturity options we again find a monotonic relation between returns and slope. However, in the longer maturity straddles we find a significant *decrease* in returns as slope increases. A six month portfolio with the most negative slope returns an average of 3.42% per month.

Our study contributes to three strands of recent literature. First, we contribute to the literature which examines the pricing of volatility in options.[5] Second, we contribute to a growing literature seeking to understand the cross-sectional pricing of individual options returns.[6] Finally, our study extends the literature on the term structure of risk premia by improving our understanding of the dynamics of volatility across the term structure.

We differ from previous literature on returns in the cross-section of options in that we study returns across a range of maturities.[7] Specifically we study how option (straddle) returns depend upon volatility term structure in the cross-section and across maturities. We show that the relation between volatility term structure and future returns varies across maturities of the options we examine. While short maturity options exhibit a positive relation between term structure slope and subsequent returns, the longer maturity straddles exhibit a negative

[5] Seminal studies include Coval and Shumway (2001), Bakshi and Kapadia (2003a), Bakshi, Kapadia, and Madan (2003), and Jackwerth and Rubinstein (1996)

[6] See Goyal and Saretto (2009), Carr and Wu (2009), Driessen, Maenhout, and Vilkov (2009), Bakshi and Kapadia (2003b), Cao and Han (2013), Vasquez (2015), Boyer and Vorkink (2014), and Bali and Murray (2013).

[7] See e.g. Bakshi and Kapadia (2003b), Boyer and Vorkink (2014), Bali and Murray (2013), Cao and Han (2013), and Goyal and Saretto (2009).

relation. This pattern is closely related to the implied volatility dynamics we uncover in the first part of our study.

Our study proceeds as follows. Section 1.2 describes the data and methodology for forming the portfolios. Section 1.3 examines the term structure dynamics, and in Section 1.4 we describe a framework based on our analysis and propose a number of trading strategies. Section 1.5 reviews the returns of these strategies which verify our analysis. Section 1.6 performs robustness checks. Section 1.7 concludes the first chapter.

1.2 Data and Methodology

The OptionMetrics Ivy Database is our source for all equity options prices, the prices of the underlying equities, and risk-free rates. The Database also supplies realized volatility data and implied volatility surfaces which we use as a robustness check for our calculations of annualized realized volatility and slope of the volatility term structure, respectively. Our dataset includes all U.S. equity options from January, 1996 through August, 2015. We follow the Goyal and Saretto (2009) procedures in forming portfolios. The day following the standard monthly options expiration on the third Friday of each month, typically a Monday, we form portfolios of options straddles. On this date, we deem all options ineligible from inclusion in portfolios if they violate arbitrage conditions or the underlying equity price is less than $10. We then identify the put and call option for each equity, for each expiration from one to six months, which is closest to at-the-money (ATM), as long as the delta is between 0.35 (-0.35) and 0.65 (-0.65) for the call (put).[8] If, for each equity, for each expiration, both a put and call option exists which meets the above conditions, then a straddle for that equity for that expiration will be included in a portfolio. Since the procedure for the listing of equity options is not consistent in the cross-section or over time, the number of straddles included

[8]The deltas are also taken from the OptionsMetrics Database. Option deltas are calculated in OptionsMetrics using a proprietary algorithm based on the Cox-Ross-Rubinstein binomial model.

across maturities will vary for each firm and over time, as will the number of straddles in each portfolio. While we include statistics for portfolios of options with maturities of one through six months, our study focuses on the performance of portfolios holding one month and six month options. Even though individual equity options are more thinly traded than index options, we only look at ATM options *and* by taking portfolio averages, we hope to mitigate issues which may arise due to illiquidity and noisy prices.

After identifying the ATM straddles eligible for inclusion, we form portfolios based on the slope of the implied volatility term structure. For all options, we use the implied volatilities provided by OptionMetrics.[9] We define the slope of the term structure as follows. On each formation date, the day following the standard options expiration, we identify for each equity the ATM straddle with the shortest maturity between six months and one year. We use the implied volatility of this straddle, defined as the average of the implied volatilities of the put and call, as the six month implied volatility. We use this measure, and the implied volatility of the one month straddle, to calculate the slope as determined by the percentage difference between the implied volatilities of the straddle, $\frac{1mIV}{6mIV} - 1$. When determining the slope of the term structure, we allow for the flexibility of maturity in the six month measure due to the fact that for each month, an equity may not have six month options due to the calendar listing cycle to which an equity is assigned. The options of each equity are assigned to one of three sequential cycles: January, February, and March. Regardless of the cycle, options are listed for the first two monthly expirations.[10] Beyond the front two months, the expirations listed vary. For example, on the first trading day of the year, January and February options are listed for all equities. The next expirations listed for options of the January cycle are April and July, the first month of the following quarters; for the February cycle, the next listings are May and August, the second

[9]As with the option deltas, the implied volatilities are determined in OptionsMetrics using a proprietary algorithm based on the Cox-Ross-Rubinstein binomial model.

[10]In addition, equities with the most heavily traded options may list additional expirations.

month of the following quarters. Those equities in the March cycle find March and June options listed. Thus, in any one month, roughly 33% of equities list a six month option, with the remainder listing a seven or eight month option. In calculating the slope, we use the shortest maturity six months or longer, and so the slopes for any month actually include one month - six month, one month - seven month, and one month - eight month slopes. Using this measure each month for an equity, we place all eligible straddles for that equity into a decile and maturity bucket. Decile 1 holds straddles with the most upward-sloping term structure, or positive slope; Decile 10 contains those with the most inverted, downward sloping, or negative slope. We view the returns of the portfolios across both decile and maturity to examine the interaction of the two. Consistent with Goyal and Saretto (2009), these portfolios are created the day following expiration; opening prices for the options, the midpoint between the closing bid and ask, are taken the day following portfolio formation. Typically, then, opening trades for the portfolios are executed on the close the Tuesday after expiration. For one month straddles held to expiration, closing prices are calculated as the absolute value of the difference between the strike price and the stock price on expiration. For one month options held for two weeks, the exit prices of the straddles used are the midpoint of the closing bid and ask prices two weeks from the prior expiration. For the two through six month straddles, the exit prices of the straddles are the midpoint of the bid and ask of the closing prices on the following expiration day. Over the period of January, 1996 through August, 2015, our analysis includes 924,952 straddles across all maturities, representing 7,076 equities. Using the implied volatilities of these straddles, we examine the dynamics of the term structure of equity options.

1.3 Term Structure Dynamics

Figure 1 and Table 1 are the starting points of our analysis. The volatility risk premiums for all portfolios are reported in Table 1. Each month on the formation date, ATM straddles are sorted into portfolios on the basis of volatility term structure. For each straddle, the $VRP = \frac{IV-RV}{RV}$, where the realized volatility of the underlying is determined *ex ante* using daily returns over a period equal to the straddle horizon. This measure differs slightly from that typically used to quantify VRP in that we examine the ratio of option-implied volatility (IV) to realized volatility (RV). This measure removes biases that can arise due to underlying assets tending to have widely disparate volatilities in the cross-section. This normalization of the risk premium of course is not necessary when studying volatility risk premia in the index because the underlying asset has a stable, mean reverting volatility process. In the cross-section of stocks however, there is wide variation in volatility of the underlying. This necessitates such a normalization in order to avoid single firms contributing disproportionately to a portfolio's average implied volatility. Portfolio VRP is defined as the average VRPs of the equities within a portfolio. Figure 1 plots unconditional index and equity VRP, and VRP for each conditioned on term structure. While most of our analysis sorts equity options into ten portfolios cross-sectionally, we sort into five portfolios here to be consistent with our index sort. In order to conserve space within the figure, we plot only the two extreme quintiles' average volatility risk premia. For more detailed results, Table 1 reports monthly time series averages within all portfolios sorted into deciles based upon term structure.

Figure 1 depicts the VRPs over different maturities. The first figure plots the average index and equity portfolio VRPs. For all maturities, the VRPs for both index and equity are positive; the equity portfolio VRPs are positive for one through five month maturities, dipping slightly negative for the six month maturity (-0.02). This is consistent with a negative price of volatility and a positive volatility risk premium. It is well known that the volatility risk premium implied by index options is large and positive on average, while the premia for equities is smaller. This is seen as well: the equity portfolio VRP is less than that of the index. Unlike the index, the equity portfolio VRP is downward sloping: longer maturities carry a lower premium.

Figure 1 shows that the differences in the premia also depend upon the slope of the implied volatility term structure, similar to the analysis of Johnson (2016). When the *index* term structure is upward sloping (Quintile 1), the volatility risk premia is large across all maturities. When the term structure is inverted, the volatility risk premia inherent in the index is significantly smaller. For equities, however, the patterns are strikingly dissimilar to those found in the index. While the risk premia is large when the curve is upward sloping in the index, the portfolio measure is lower across all maturities for the equity portfolio. The largest premia for the individual equities is in the one month options with the most inverted term structure. This contrasts with the premia in the index where the inverted term structure corresponds to the smallest premia among the one month options. In Quintile 5, in the individual options, the average volatility risk premia are steeply decreasing in maturity. Surprisingly, the six month options with the most inverted term structure actually have a negative volatility risk premium on average. This of course contrasts with the commonly held assertion that investors are willing to pay a premium to avoid exposure to volatility risk. Figure 1 also shows that the individual and index volatility premia differ in that index premia tend to decrease as the term structure becomes more inverted, regardless of maturity. For the individual options, we see *increasing* premia as the term structure increases for the shorter maturity options and the pattern slowly reverses as maturity increases. For the five and six month options, the premia decrease as term structure becomes more inverted. The remainder of the paper aims to improve our understanding of the patterns depicted in Figure 1.

Differences between implied volatility and realized volatility are approximate risk premia. Table 1 shows a nearly monotonic relationship across deciles for the one and six month maturities. All one month options portfolios exhibit large VRP. This is in line with the notion that investors are averse to bearing volatility and require a premium for bearing it. In the one month options, VRP is strongly increasing in term structure inversion. As the maturity increases, we see a gradual shift in the VRP pattern, as average VRP is virtually flat between Deciles 1 and 10 for the three and four month options. In the five and six month options, the VRPs decrease in term structure inversion, and the six month implied volatilities of the equities with most inverted term structures (Decile 10) actually exhibit a negative risk premium: -3.30%. A negative VRP corresponds to realized volatility exceeding implied volatility on average. This implies a positive price of volatility which is difficult to reconcile with economic theory and recent empirical work of Ang, Hodrick, Xing, and Zhang (2006), Rosenberg and Engle (2002) and Chang, Christoffersen, and Jacobs (2013).

While Figure 1 and Table 1 describe unconditional averages, our analysis focuses on the dynamics of term structure. In order to get a sense of how the term structure evolves, Figure 2 depicts the time series of average implied volatilities used in the construction of our measures of term structure slope. In order to conserve space, we only show the implied volatilities from the two extreme slope deciles: the average one month and six month implied volatilities for at-the-money options on stocks within the top and bottom 10 percent each month, as defined by $\frac{1mIV}{6mIV}$. In the first panel, we see that the one month implied volatility is always higher in the most inverted decile (10) than in the least inverted decile (1). Furthermore, the difference is significant over most of the sample. The second panel shows the time series of six month implied volatilities in Deciles 1 and 10. While the six month implied volatility in Decile 10 exceeds that of Decile 1 on average, the two do not exhibit much of a spread through most of the sample. This suggests that most of the variation in term structure is driven by variation in the short maturity implied volatility. Both series exhibit spikes around the dot com crash of 2000 and the financial crisis of 2008. The last panel shows the slope of volatility term structure measured each month in the sample, for the two extreme deciles, and the slope of the S&P 500 Index. The Index term structure more closely follows that of Decile 1 over the entire period, but during spikes will approach the measure of Decile 10. The average implied volatility term structure slope does not exhibit the same pattern, suggesting that average volatility term structure is not simply a measure of market volatility.

To understand how the distributional properties of implied volatility depend upon term structure and time to maturity, Table 2 reports the means, standard deviations, and skewness of the implied volatilities of the portfolios formed using the procedure described above. Each month, the day after the standard monthly expiration, ATM straddles are sorted into portfolios by maturity and the slope of the term structure. Decile 1 holds ATM straddles with the most upward sloping term structure; Decile 10 holds straddles with the most inverted, or downward sloping term structure. Table 2 uses the average implied volatility each month of the ATM straddles to calculate these summary statistics. Thus, Panel A reports the average implied volatilities over time of the portfolio's average implied volatilities calculated each month; Panels B and C hold the standard deviation and skewness, respectively, over time of the portfolio's average implied volatilities calculated each month.

By separately measuring average means, standard deviations and skewness of each portfolios' implied volatility and by examining the measures for options of different maturities, we are able to get a clear picture of the strong patterns that exist in the term structure of implied volatilities. The far right column in each panel shows summary statistics when we aggregate all deciles. Similarly, the bottom row reports summary statistics for each decile of term structure slope when aggregated across all times to maturity.

In Panel A, if we look only at the column that aggregates across all deciles, we see that average implied volatility is monotonically decreasing in time to maturity. However, this column shows a relatively small spread in the average implied volatilities of about 2.6 percentage points. If we look across the decile portfolios however, we observe that the monotonic pattern is strongest in Decile 10, the most negatively sloped term structure. The spread between the six month and one month average implied volatilities in the tenth decile is more than 12 percentage points, nearly five times the spread we see when we aggregate across deciles. Notice that in the extreme upward sloping decile, the spread is much smaller than in the extreme inverted decile. By construction Decile 1 has higher six month average implied volatility than the one month. This pattern is also monotonic in time to maturity which is not a tautology.

Similarly, if average implied volatility is aggregated across all maturities, we see that portfolios of options with the most negatively sloped volatility term structure have higher implied volatilities on average. The difference is roughly 10.5 percentage points. However, by looking at the top row, it becomes clear that the spread is driven by the shorter maturity options. The spread in the one month options is approximately twice that of the aggregated spread we see in the bottom row. Furthermore, the spread is monotonically decreasing in maturity. This suggests that when we see inverted term structure, it tends to be driven by large increases in short term volatility as opposed to decreasing six month implied volatility. Interestingly, the six month average implied volatilities also increase as the term structure becomes inverted. Of course the increase is much larger for the one month options than for the six month options.

Panel B of Table 2 shows that time series standard deviations of annualized implied volatilities tend to be larger the more negative the slope. Furthermore, while average time series standard deviations tend to increase monotonically as time to maturity decreases, the spread between standard deviations of Decile 10 and Decile 1 is most exaggerated in the one month options. As in Panel A, this suggests that the driver of term structure is due to movement in the short term implied volatility. Importantly for trading strategies we will investigate in Section 1.5, the distribution of implied volatility tends to be positively skewed for all deciles and for all times to maturity. The skewness is largest for the most inverted term structures. Furthermore, the spread between skewness in Decile 10 (inverted) and Decile 1 (upward sloping) tends to be larger for short term options. The skewness patterns we've shown will be explicitly incorporated into our framework in Section

1.4 as they are central to understanding how one can implement trading strategies that exploit dynamics in the term structure curve.

From the summary statistics, a picture begins to emerge as to how the term structure changes. Given the spread between Deciles 1 and 10 in the one month mean and standard deviation of implied volatility, the short end drives the term structure. Table 3 shows the time series relationship between percent changes in short term (one month) implied volatility and long term (six month) implied volatility. The changes in one month and six month volatilities are calculated for each firm, and then the changes are averaged within each portfolio. Table 3 reports the results of regressing the change in one month volatility on the change in six month volatility for each portfolio and for the entire sample:

$$\frac{IV_{i,t}^{1m}}{IV_{i,t-1}^{1m}} - 1 = cons_i + b_{6mIV,t}\left(\frac{IV_{i,t}^{6m}}{IV_{i,t-1}^{6m}} - 1\right) + \epsilon_{i,t}. \tag{1.1}$$

Across all deciles, we see highly significant loadings, $b_{6mIV,t}$. The loadings are all positive and in excess of one meaning that changes in six month implied volatility are associated with *larger* changes in one month implied volatility. We can think of one month implied volatility as exhibiting dynamics similar to a levered version of the six month implied volatility. There is a monotonic pattern to the relation between term structure inversion and regression coefficient $b_{6mIV,t}$, suggesting that the magnification of movements from six month implied volatility to one month implied volatility is increasing in term structure inversion. For the most inverted (tenth) decile, a one percent change in six month implied volatility is associated with a 1.734 percent change in one month implied volatility on average. While the two are highly correlated, we see much larger swings in implied volatility of one month options than in six month options. This is especially true in the decile of options with the most inverted term structures. Since we know from Table 2, the distributions of implied volatilities are positively skewed, this means that we tend to see small increases in six month implied volatilities and these are associated with larger increases in one month implied volatilities.

We see that the movements of one month implied volatility act as the driver of the volatility spread. We then examine the average realized volatility of each portfolio for the period leading up to the formation date, as compared to the average implied volatility, to get a snapshot of the relationship between realized and implied volatility. While Table 1 measures the relationship between realized and implied volatility averaged over time, Table 4 examines the relationship between realized and implied volatility. In order to conserve space, we report the results for only the shortest (one month) and longest (six month) maturities in our sample. Each month, within each decile, the implied volatilities of the ATM straddles are regressed on the realized volatilities of the underlying, calculated using past daily closes over a fixed horizon. Each of the resulting monthly cross-sectional regression coefficients are then averaged over the entire time series.

We examine past horizons of one month and one year to determine the effects of long term and short term measures of past realized volatility on current implied volatility. For each firm, at each date we run the following regressions for short and long term realized volatility respectively:

$$IV_{i,t} = cons_i + b_{i,RV} RV_{i,t-1} + \epsilon_{i,t}, \tag{1.2}$$

$$IV_{i,t} = cons_i + b_{i,RV} RV_{i,t-12} + \epsilon_{i,t}, \tag{1.3}$$

where $IV_{i,t}$ and $RV_{i,t}$ denote implied and realized volatility of firm i at month t respectively. Table 4 averages the coefficients, standard errors, and R^2s of these regressions over the sample period within each decile. The regression coefficients from Equation (1.2) are positive and highly significant across all deciles, for both measures of realized volatility and for both maturities.

For one month implied volatility, Panel A shows that there isn't much variation in slope coefficients when we regress one month implied volatility on the previous month's realized volatility. While the slope coefficient generally decreases as the term structure becomes inverted, the variation in point estimates is not economically significant. The R^2 of each regression is shown to generally decrease in term structure inversion, however, most of this pattern can be attributed to the substantially smaller R^2 for Decile 10 whereas little variation exists between the R^2s for the other nine deciles.

Perhaps surprisingly, the coefficients reported in Panel B suggest that short maturity implied volatility is more sensitive to realized volatility measured over the previous year than it is to measures from the previous month. Furthermore, the sensitivities are monotonically increasing in term structure inversion suggesting that when the term structure is most inverted, short term implied volatility is most sensitive to long term measures of past volatility in the underlying. In addition to the larger coefficients, we also see that in univariate regressions, the proportion of variation explained by the long term measure of realized volatility exceeds that explained by the short term measure. This is contradictory to the common view that short maturity implied volatility is more sensitive to recent changes in realized volatility than it is to the longer term, more stable measure of realized volatility.[11]

Panels C and D of Table 4 report the results of regressing long term maturity implied volatility on the two measures of realized volatility. Again, all slope coefficients are positive and significant, and some interesting patterns emerge. In Panel C, where we regress long term implied volatility on the previous one month's realized volatility, we see much more variation across slope deciles than we do in Panel A, which reports the analogous regressions using short term implied volatility. While Decile 1 implied volatility is very sensitive to the past month's realized volatility, the most inverted decile shows a slope coefficient just over half that of Decile 1. The R^2 measures show some decline as term structure becomes more inverted but the drop off is not as large as the equivalent pattern from Panel A. While the short term implied volatility becomes slightly less sensitive to one

[11] See for example Jones and Wang (2012).

month previous realized volatility when the curve becomes inverted, the long term implied volatility becomes much less sensitive. However, when the curve is least inverted, the long term implied volatility is *more* sensitive to the previous one month's volatility than is the short term implied volatility.

In Panel D where we examine the relation between the previous year's realized volatility and long term maturity implied volatility we see higher slope coefficients as compared with Panel C. This is consistent with the finding for the one month implied volatility in Panels A and B. However, here we see a weak decreasing pattern in the slope coefficients as the term structure becomes more inverted. While this contrasts with the increasing pattern seen in Panel B, it is more in line with the general intuition that as the term structure becomes inverted, long term maturity implied volatility is less sensitive to previous realized volatility measured over long horizons.

We extend our analysis of the impact of realized volatility to include the term structure itself. Table 5 reports the results of cross-sectional regressions similar to those in Table 4 except with term structure slope as the dependent variable. Each month, within each decile, term structure slopes are regressed on the realized volatilities of the underlying, calculated using past daily returns over a fixed horizon. Each of the resulting monthly cross-sectional regression coefficients are then averaged over the entire time series.

Panel A reports the results for regressions with realized volatility calculated using the returns of the underlying over the previous month. Panel B reports the results from similar regressions where realized volatility is measured over the previous year's daily returns. Recall that our term structure measure is a percentage difference between long and short term maturity implied volatility so that we are essentially controlling for the level of implied volatility. In both regressions we see a monotonic decline in both slope coefficients and R^2s as we move from least inverted to most inverted term structure. This suggests that as the term structure becomes more inverted, the slope is less determined by past realized volatility. If we compare across Panels A and B, we notice that all of the slope coefficients and R^2s in Panel B are smaller than those in Panel A. This suggests that across all slope deciles, the long term past realized volatility is less of a determinant of term structure. The results here, the regressions in Table 4 and the VRPs in Table 1 together show that as the term structure inverts, it becomes less a function of realized volatility. The increase in implied volatility outpaces realized volatility for one month options, the R^2 decrease from Decile 1 to Decile 10, and the term structure becomes much less sensitive to realized volatility as it inverts.

The results presented thus far suggest that short maturity implied volatility tends to drive the movement which in turn drives changes in the term structure. In Table 6 we examine how this relationship depends upon a lagged relationship between long and short maturity implied volatility. In Table 6 we examine the dynamic relationship between two month and one month IV and six month and one month IV. The day after the standard options expiration, we first identify one, two and six month ATM straddles for firms, subject to standard filters. We then sort the straddles on the basis of the slope of the term structure into five quintiles, and calculate the averages of the one, two and six month IVs for each month for each maturity.

Next, we measure the percentage change in one month implied volatility over the subsequent two weeks. Here, we again use an ATM measure of implied volatility in order to isolate the term structure dynamics and remove any impact skew may play. As a result, we are not necessarily comparing the implied volatility of the straddle at time t_0 with the implied volatility of that same straddle at time t_1. Based on the percentage change in one month ATM volatility, we sort into another five quintiles within each of the term structure quintiles. The sorting enables us to examine how two and six month implied volatility relates to term structure slope *depending upon* how the short term implied volatility evolves following the observation of term structure slope. When we first observe term structure slope, this measure tells us the relation between one month and six month implied volatility.

Suppose term structure is inverted at our formation date so that short term implied volatility exceeds long term volatility. Over the course of the next month, does implied volatility on the short term options decrease? This could be the case for instance if the term structure we observe is due to overreaction in the more volatile, one month options. If short term implied volatility continues to increase over the course of the month, it is more likely that the inversion was the result of some persistent shock to risk-neutral volatility. Hence this double sorting allows us to observe how the joint dynamics of short and long term implied volatility depend upon the term structure and persistence of implied volatility.

In Section 1.5, we will examine straddle trading strategies based upon one month holding periods. In order to understand the monthly straddle returns, in Table 6 we examine *intra monthly* implied volatility data within each of the 25 portfolios. We measure implied volatilities every two weeks within each portfolio. By looking at higher frequency data, our goal is to understand the joint dynamics of short and long term volatility within each of the 25 double sorted portfolios.

Within each portfolio, at time t_1 we regress two and six month ATM implied volatility on contemporaneous one month implied volatility and the two-week lagged implied volatility of the one month options calculated at formation of the portfolios:

$$IV_t^{6m} = c + b_1 IV_t^{1m} + b_2 IV_{t-1}^{1m} + \epsilon_t. \tag{1.4}$$

For each of the 25 portfolios double sorted by term structure and percentage change in subsequent implied volatility, we separately report the results of regressions described by Equation (1.4) in Table 6. We observe very strong patterns across both dimensions of our double sorting: term structure slope and subsequent implied volatility percentage change. These dynamics are, to the best of our knowledge, new to the literature.

By regressing six month implied volatility on one month implied volatility alone, we expect to be able to describe a large part of the variation in our dependent variable. In our regressions we include the additional lagged as well as the contemporaneous 1 month implied volatility. Across all but one of the 25 portfolios, the regression R^2s exceed 92%. The portfolio with the steepest upward sloped term structure and the lowest subsequent percentage change in implied volatility (Portfolio (1,1)) has an R^2 of only 82.2%. In each of the portfolios, the parameters of the regression equations are estimated with a high degree of precision.

We observe several novel results within Table 6. The patterns relating dynamics across portfolios are important for informing the trading strategies we will describe in Section 1.5. First, we find that regardless of the percentage change in implied volatility, the sensitivity of six month implied volatility to contemporaneous one month implied volatility monotonically decreases in term structure inversion. On the other hand, the sensitivity of six month to the (two week) lagged one month implied volatility is monotonically *increasing* in term structure inversion regardless of subsequent changes in implied volatility. That is, within each implied volatility change quintile, six month implied volatility's sensitivity to contemporaneous short term volatility decreases in term structure inversion while the sensitivity to lagged short term inversion increases in term structure inversion. More succinctly, the more inverted the term structure is, the more six month implied volatility lags behind one month implied volatility. Within each of the five quintiles sorted on implied volatility we have strict monotonicity. This combined with the fact that the regression coefficients are estimated with strong precision suggests that the relationship is very robust.

In addition to the patterns across term structure inversion, we also look across the portfolios sorted on implied volatility changes. Interestingly, the pattern described in the previous paragraph is stronger for portfolios with the larger change in subsequent one month implied volatility. The relationship is monotonic in the following sense: within each term structure portfolio, the sensitivity of long term implied volatility to contemporaneous short term implied volatility is decreasing in subsequent short term implied volatility change. On the other hand the sensitivity to the lagged short term implied volatility is *increasing* as we move down the table from Quintile 1 to Quintile 5. In fact, for the 5-5 Portfolio which has the most inverted term structure and the largest subsequent percentage change in short term volatility, six month implied volatility is actually *more* sensitive to lagged than it is to contemporaneous short term volatility.

When we examine the regressions of two month ATM implied volatility on contemporaneous and lagged one month ATM implied volatility, we find the same pattern, although the sensitivity to contemporaneous one month IV remains higher across term structure and implied volatility change. As expected, R^2 of these regressions are higher, as the relationship is tighter between two and one month volatility. All are greater than 0.95, with the exception of the 1-1 Portfolio, with an R^2 of 0.949. The sensitivity to contemporaneous (lagged) one month IV is decreasing (increasing) across both term structure and IV change. In the 5-5 Portfolio, two month ATM IV has a loading of 0.681 on one month ATM IV, compared to 0.359 for the six month ATM IV.

Overall, the results of Table 6 suggest that when implied volatility term structure is more inverted, the long term implied volatility tends to lag behind short term volatility: the loading on contemporaneous volatility is lowest when the term structure is most inverted. When the cause of the term structure inversion is found to be short-lived, this lagged relationship is weaker. In this case, loading on contemporaneous volatility is highest among the five quintiles of IV change. On the other hand, if the shock to short term volatility that caused term structure inversion persists, long-term volatility continues to lag, as the loading on lagged 1m IV (0.471) is greater than that of the contemporaneous IV (0.359). We can thus think of the long term implied volatility as taking a “wait and see” stance. If the shock is short-lived, then long term volatility is less affected by the shock, as its initial and subsequent reactions are muted. Conversely, if the shock persists, long term volatility continues to react cautiously, loading more on lagged volatility. These new results are important for our understanding of the dynamic nature of the implied volatility term structure. Below we investigate whether this relationship can be exploited in a profitable trading strategy.

1.4 Framework

In this section we encapsulate the basic properties of long and short term implied volatility uncovered above. In Section 1.5, we examine trading strategies as a verification of our findings. While we take the information presented in Tables 2 through 6 as the basis for our framework, we use only the most salient features. As a result, the framework we describe below is intentionally very simple in order to plainly show where potential for profitable trading strategies emerge.

Here, we assume that when we see the term structure invert, there has been some sort of positive shock to implied volatility in the pricing of short term (one month) options. Of course it is a simplification to assume that the inverted term structure is due only to a positive shock to implied volatility of short term options. However, the summary statistics in Table 2 show that the majority of movement in implied volatility resulting in inverted term structure is due to the short term options. To see this, note that for the one month options, the difference between the average IV for the least inverted and most inverted volatility term structure is more than 20% versus a difference of less than 5% in the long term options. The fact that Table 2b shows time series standard deviations of average implied volatilities are much larger for the one month options than for the six month options further informs our simplifying assumption that term structure inversion is due solely to movement in implied volatilities to one month options.

In Panel C of Table 2, we see that average implied volatility has a positively skewed distribution for all bins and the skewness is greatest among the most inverted (Decile 10). For this reason, when we model shocks to implied volatility of firms with inverted term structure, we will only look at positive shocks to volatility. As a result our simplified distributions will have only two levels: a baseline and high level of implied volatility. This is the simplest way for us to model a positively skewed distribution, where the baseline volatility has a larger probability mass than that of the high level. Let V_B^s denote the baseline volatility and let V_H^s denote the high level volatility of short term options, where $V_B^s < V_H^s$. We will further assume that returns to straddles are exactly replicated by buying and selling the level of implied volatility. So, if we buy a short term straddle at time t and sell it at time $t+1$, then our straddle returns are given by $(V_{t+1}^s - V_t^s)/V_t^s$, where V_t^s denotes short term (1 month) implied volatility at time t.

Here, an inverted term structure is driven by a shock to only short term volatility. We further assume that if the shock ultimately persists, then the long term implied volatility will adjust accordingly, after it is determined that the shock was not noise. Importantly, this revelation takes place sometime after we first observe the inverted term structure but before the end of the holding period in which we trade. This is a simplification of the results presented in Table 6 where we show that when the term structure becomes inverted and we witness a persistent shock to short term implied volatility, six month implied volatility tends to load more heavily on lagged short term implied volatility. On the other hand, when term structure is inverted but the shock turns out not to be persistent, six month implied volatility tends to load less heavily on lagged short term implied volatility.

Assume that we observe a shock to short term volatility, or equivalently, an inverted term structure of volatility. Given the inverted term structure curve, the probability that the shock causing the inversion is fundamental (as opposed to just noise) we denote by p_f. The probability of the shock being pure noise is $1 - p_f$. The trading strategies we describe are based upon first observing that a shock has occurred, and then buying and selling option straddles accordingly.

If we observe an inverted term structure today, then at the end of our holding period, we either realize that the shock was just noise, in which case one month implied volatility reverts to its baseline level V_B^s, or, if the shock turns out to be fundamental, then the volatility remains at the high level, V_H^s. Similarly, six month implied volatility has a skewed distribution (see Table 2) and we assume that it has a baseline and high level $V_B^L < V_H^L$, where V_B^L denotes the baseline and

V_H^L denotes the high level for long term options.

There are two trading strategies we examine once we observe an inverted term structure. Strategy 1 buys short term straddles. Strategy 2 buys long term straddles. Strategy 1 realizes negative returns when the shock we observe turns out to be noise. Strategy 2 makes money when the shock persists.

The expected returns to Strategy 1 are:

$$\mathbb{E}(R_1) = 0 \cdot p_f + (1 - p_f)\frac{(V_B^s - V_H^s)}{V_H^s} < 0.$$

The expected returns to Strategy 2 are given by:

$$\mathbb{E}(R_2) = p_f \frac{(V_H^L - V_B^L)}{V_B^L} + 0 \cdot (1 - p_f) > 0.$$

In terms of comparative statics, both strategies will see a larger return when the spread between V_H and V_B is higher. Also, if the probability of a shock turning out to be fundamental (p_f) is large, then Strategy 2 has a higher (positive) expected return. On the other hand the returns to Strategy 1 are most negative when if the probability of a shock being fundamental (p_f) is low.

1.5 Trading

Given the joint dynamics we've shown for short and long term implied volatility, we next investigate whether these translate to profitable trading strategies using option straddles. Based upon our framework from Section 1.4 for understanding the patterns observed in the implied volatility data, we propose trading strategies which we show bear out the predictions of our framework.

Table 7 reports the returns and standard errors for straddle portfolios of different maturities and the long/short portfolio which owns Portfolio 10 and shorts Portfolio 1. Sharpe Ratios are included for the one and six month options portfolios and the calendar spread portfolios. The holding period for all is one month, with the exception of the first stanza, which shows the returns of portfolios of one month straddles held for two weeks. The returns for both versions of the one month portfolios echo the findings of Vasquez (2015): the returns on straddle positions decrease as the term structure becomes more inverted. Holding the Decile 10 portfolio to expiry costs 11.85% monthly, while owning Decile 1 portfolio returns 2.55% per month. A portfolio which buys Decile 1, and sells Decile 10 returns 14.41% monthly, posting a Sharpe Ratio of 2.723. While the returns of Decile 1 are not statistically significant, those of Decile 10 and the long/short position are highly significant. As discussed above, as term structure becomes more inverted, the change in implied volatility outpaces that of realized volatility; one interpretation is the implied volatility is overreacting to the movement of the underlying.

The returns for the two month options generally follow the pattern seen in the one month options. While not monotonic, the returns decrease moving from Decile 1 to 10. The Decile 1 portfolio returns 2.46%, while Decile 10 loses 45 bps per month. A portfolio that is long Decile 1 and short Decile 10 returns 2.91% monthly, and is highly significant. Throughout the paper, we include two month option portfolios as a short term strategy alternative to the one month straddles. We do this to ameliorate any concerns that the abnormally large returns in the one month options are the result of biases arising around the time of option expirations.

For the three to five month portfolios, a change in sign of the 10-1 Portfolios is seen. For the long/short portfolios with one and two month maturities, a positive return is generated if we *buy* Portfolio 1 and *sell* Portfolio 10. For spread portfolios with maturities of four and five months, the opposite position is needed to post a positive return. The 10-1, four month Portfolio (long Decile 10, short Decile 1) earns 0.58% per month and is statistically significant at the 10% level; the 10-1, five month Portfolio posts a significant 2.14% monthly return. In addition, the five month returns increase monotonically across deciles, with the exception of Decile 9.

Recall from Table 2 that for portfolios of six month maturity options, implied volatilities increase as the term structure becomes more inverted. From Table 1, however, we know that the difference in implied volatilities across deciles of six month options is smaller than the average difference in realized volatility across deciles. The returns for long maturity straddle portfolios mirrors this pattern insofar as straddle returns mirror percentage changes in implied volatility and we see higher returns in Decile 10 than in Decile 1. In contrast to the findings of Vasquez (2015) for the short maturity straddles, the long maturity returns are strongly monotone and *increase* from Decile 1 to 10. Buying Portfolio 10 earns 3.42% month, is statistically significant and posts a Sharpe Ratio of 1.391. As this is a long volatility portfolio, the returns are negatively correlated to the S&P 500 Index (-0.416). The 10-1 Portfolio, while earning less than Decile 10 since Decile 1 also has positive returns, posts a higher Sharpe Ratio, 1.697, due to the lower volatility of the spread portfolio.

In practice, a common options strategy is the calendar, or time spread, whereby options with the same strike but different maturities on the same underlying are bought and sold. The bottom panel in Table 7 holds the returns of calendar spreads in aggregate. For each decile, the returns represent a trade where the six month options portfolio is bought and the one month portfolio is sold. Given the dynamics seen in both the one and six month options portfolios, it is perhaps unsurprising that we see increasing monotonicity in the returns. Decile 1 loses 1.56% monthly, while the Decile 10 spread earns a significant 15.35% per month, with a Sharpe Ratio of 3.123. Finally, a calendar spread spread: a position which buys the calendar spread of Decile 10 and sells that of Decile 1 (buying six month, Decile 10, selling one month, Decile 10; selling six month, Decile 1, buying one month, Decile 1) returns 16.90%, with a Sharpe Ratio of 3.312.

Figure 3 shows the monthly returns to the one, two, and six month long/short straddle portfolios based upon term structure slope. The return spikes seen for the one month portfolio coincide with market deciles. The portfolio formed after the August 2001 expiration posts the largest monthly loss, 94.5%, for the sample.

Other spikes occur during the financial crisis, the European debt crisis, and the mini-flash crash in August, 2015. During volatility spikes, then, the losses from shorting the undervalued options in Decile 1 outpace the gains from owning the overvalued options in Decile 10. The returns of the two month portfolio are highly correlated (0.82) to those of the one month portfolio, as in both cases Decile 1 is bought and Decile 10 is sold, and as shown above the dynamics of the two are similar. In contrast, the correlation of the six month returns to the one month is -0.28.

Returning to our framework, we expect the returns of the one month straddles to be most negative when the term structure is inverted and the volatility shock turns out to be transitory. And, if the shock persists, the returns seen are muted, as implied volatility already is elevated. In contrast, if the volatility shock has no follow through, we expect the losses on the six month straddles to be mollified as there was an underreaction relative to the front part of the curve. We test our model by performing an *ex post* double sort on returns. The day after the standard options expiration, we identify one, two and six month ATM straddles for firms, subject to standard filters. We then sort the straddles on the basis of the slope of the term structure into five quintiles, and hold the positions for one month. After one month, we sort the portfolios into three buckets, based on the average percentage change in realized volatility for the underlying firms over the course of the month-long holding period. Portfolio sorting exercises are typically used as a model free way to test whether a premium is earned via a trading strategy as a result of bearing risk. The sorting we do in Table 8 is obviously not meant to analyze a trading strategy as the second sort is done *ex post*. We include the *ex post* sorting procedure as a way to further analyze the predictions of our simple model of the dynamics of implied volatility. Table 8 helps us understand from where the returns described in Table 7 come.

The columns of Table 8 represent quintile portfolios based upon the term structure slope: column one represents least inverted while column five represents most inverted. The last column contains the returns of a 5-1 Portfolio, which is long Portfolio 5 and shorts Portfolio 1. The three rows within each panel represent the *ex post* sorting by percentage change in realized volatility of the underlying stock: within the five deciles, the first row represents the averages of those stocks whose percentage change in realized volatility is smallest while the third row represents those with the largest percentage change in realized volatility. Finally, the intersection of the right-most column with the final row measures the return of a portfolio which is long the 5-1 Portfolio of Δ RV Bucket 3 and short the 5-1 Portfolio of Δ RV Bucket 1, where Δ RV denotes the *percentage* change in realized volatility. This portfolio buys the high minus low portfolio in the highest Δ RV tercile and shorts the high minus low portfolio in the lowest Δ RV tercile.

We can think of the double sorted portfolios as a model free way of examining how returns vary across straddles when we vary both term structure slope and percentage changes in subsequent realized volatility. The 5-1 Portfolios represent differences in returns due to differences in term structure slope, controlling for ΔRV terciles. Similarly, differences along the ΔRV columns show how straddle returns vary *within* quintiles defined by term structure slope. The bottom row, right most column which reports the difference in the long short portfolios across Δ RV tercile can be interpreted as a nonparametric measure of the interaction between term structure slope and Δ RV: it measures how variation in returns across term structure slope will vary as Δ RV varies. The analogous regression would regress straddle returns on term structure slope, ΔRV and an interaction term:

$$r^s = a + \beta_1 TS + \beta_2 \Delta RV + \beta_3 TS \cdot \Delta RV + \epsilon, \tag{1.5}$$

where r^s denotes straddle returns and TS denotes term structure slope. In all three Panels of Table 8 we see large and significant spreads across all ΔRV and term structure portfolios. This is akin to significant point estimates of β_1 and β_2. The bottom right entry in each panel is akin to the point estimate of β_3. The advantage of the double sorts as opposed to the regression equation is that the sorting does not rely on any parametric assumption. The regression equation in (1.5) on the other hand assumes a very specific linear relationship between straddle returns, the two explanatory variables and the interaction term.

Table 8 is similar to Table 6 in that we look at portfolios which are first sorted on volatility term structure and then, within each slope portfolio, sorted by subsequent *ex post* changes in volatility. Whereas the second sort in Table 6 is based upon one month option implied volatility, the second sort in Table 8 is based upon changes in *realized* volatility in the underlying. Table 6 is informative for understanding the dynamic relationship between short term and long term implied volatility. However, in order to compare the returns of one month, two month and six month straddles in Table 8 we measure subsequent volatility using *realized* volatility of the underlying asset rather than one month implied volatility so that there is less of a mechanical relation between returns and changes in subsequent volatility.

As we show in Table 8, the behavior of long term implied volatility depends upon whether or not volatility persists after the portfolio formation date. When our variable of interest is straddle returns, we sort on subsequent changes in realized volatility as our measure. If term structure is inverted on the sort date and realized volatility of the underlying asset grows over the subsequent month, we consider this a fundamental change in volatility that was captured by the inverted term structure. Our framework of volatility term structure dynamics suggests that if term structure becomes inverted and volatility persists then the long term straddle will see positive returns. Furthermore, if the long term straddle returns are largely reliant on a positive relation to fundamental volatility of the underlying asset, then we expect to see larger returns to the long term 5-1 strategy when Δ RV is large rather than small. This is exactly what we see in Table 8. Consistent with Table 7 the 5-1 strategy for long term volatility earns positive returns in all three Δ RV terciles, and the returns for the high minus low strategy are increasing in

Δ RV terciles. As the last column, final row shows, the difference between the 5-1 returns in the largest and smallest Δ RV deciles is both statistically and economically significant at 2.73% per month, suggesting a significant interaction between term structure slope and subsequent volatility. This is consistent with the results of Table 6 where we see that the dynamics of six month implied volatility depend upon the slope of the term structure and the contemporaneous volatility (measured by one month implied volatility). Here our sorts illustrate in nonparametric fashion an interaction effect between term structure slope and realized volatility.

Panels A and B of Table 8 report the returns for the one month and two month straddles respectively. We discuss these two panels together as the short maturity straddle returns. In both cases, the high minus low term structure portfolios earn negative returns in all three Δ RV terciles, consistent with Table 7. In neither panel is the difference between the high minus low strategy siginificantly different between the highest and lowest Δ RV terciles. We can however see a large spread between returns in Δ RV Terciles 3 and 1 within each of the term structure quintiles. This suggests that both the term structure and changes in realized volatility over the holding period are significant determinants of straddle returns. However, unlike the returns of the long maturity straddles, it does not appear that there is as significant an interaction effect between the term structure and subsequent volatility sorts. It is important to remember that the sorts used for Panels A, B and C are all exactly the same since they are based upon the underlying as opposed to the options. So the fact that we see an interaction for the six month options but not a strong interaction effect for the short term options is not due to differences in break points for the sorts. Rather this difference is due to differences in the pricing of short and long maturity options.

Surprisingly, for the one month straddles in Panel A, the high minus low portfolio returns are fairly consistent across Δ RV terciles and the point estimate are not monotonic. While there are very large spreads across Δ RV terciles, *within* each of the term structure quintiles, there does not seem to be any sign of an interaction between the term structure and realized volatility in determining straddle returns. For the two month straddle returns of Panel B, just as in Panel A, the spread in returns across the Δ RV terciles is significant for each of the five term structure portfolios. For the two month straddle returns however, there is a weak monotonic relation in the 5-1 column but the difference between the high Δ RV and low Δ RV terciles is not significant in this column. Since the sorting in all three panels of Table 8 is the same, we can confidently say that the interaction effect is stronger for the long term options than it is for the short term options.

Overall, the results presented in Table 8 suggest that the spread we observe in straddle returns based upon term structure sorts in the longer maturity options is to a large extent due to interaction between the term structure and changes in volatility of the underlying. There is a positive relationship between the term structure-based, long maturity trading strategy described in Table 7 and changes in the underlying volatility. The reason for the positive interaction is also alluded to in Table 6. There we show that the way six month implied volatility reacts to changes in short term *implied* volatility differs across portfolios formed on term structure slope. The way it varies across term structure portfolios actually depends upon subsequent changes in short term implied volatility. We see another manifestation of the interaction effect in Panel C of Table 8 where difference in long short portfolio returns across ΔRV terciles is significant.

Various measures have been proposed in the literature to examine whether options markets overreact. The measures of which we are aware do not necessarily consider specific events with respect to which we observe a reaction. Rather, short term implied volatility is compared with a longer term measure of volatility. Movements away from this long term measure have been deemed to be overreactions. The summary statistics described in Table 2 show that short term options show higher implied volatility as well as more volatile and skewed distributions of average implied volatilities. Furthermore, the dichotomy between implied volatility of short term and long term options is magnified when we look at the most inverted term structure portfolio. As a result, we examine the relation between overreaction of short term options and the implied volatility term structure.

While we witness an interaction between term structure and realized volatility in the long term options, we fail to see the same in the short-term options. We posit that the movement in the short-term options may be an overreaction to an expectation of future volatility, and so, in our model, the returns may be muted from any persistence in volatility. We examine three measures of overreaction in the short term options. The first, $\frac{1mIV}{12mRV} - 1$, compares one month IV to twelve month RV (Goyal and Saretto (2009)); the second is the VRP, measured as $\frac{1mIV}{1mRV} - 1$; and the third, $\frac{1mIV}{IV_{ave}} - 1$, compares one month IV to a six month average of one month IV. For measures one and two, realized volatility is calculated based on the daily closes of the underlying. After firms are sorted into ten portfolios according to term structure, the averages of these three measures and the term structure are calculated for each firm and then averaged for each portfolio each month. Table 9 reports the time series correlations of the three measures with that of IV term structure.

Panel A reports the average of each overreaction measure for each decile over the entire sample. All three of the measures are increasing in term structure inversion deciles. This suggests that as term structure becomes more inverted so that the one month implied volatility exceeds six month implied volatility, the overreaction measures monotonically increase. This is intuitive since the overreaction measures depend on an increase as current one month implied volatility increases, and the same is true of term structure inversion. Of course each of the overreaction measures has a different volatility measure with which to compare current one month implied volatility. In this sense, the volatility term structure can be thought of as a measure of overreaction in that it compares short term implied volatility to six month IV, a more stable measure.

Panel B describes the time series correlation between our measure of volatility term structure and each overreaction measure within each portfolio. All three of the overreaction measures are positively correlated with the volatility term structure and we see an increasing pattern in the correlations as we move from Decile 1 to Decile 10. This suggests that the inverted term structure is more correlated with measures of overreaction in short term implied volatility, and is explored in Vasquez (2015). To test whether the movement in short-term volatility may be an overreaction, we take the monthly portfolio returns summarized in Table 7, and regress them on the returns of an "under" and "over" portfolio. The "under" and "over" portfolios are formed by sorting eligible straddles according to the overreaction measure $\frac{1mIV}{12mRV} - 1$ from Goyal and Saretto (2009). The "under" portfolio consists of firms in Decile 1: underreaction. The "over" portfolio consists of firms in Decile 10: overreaction. The "overunder" factor used to examine the 10-1 returns is a long-short portfolio which owns the "over" and shorts the "under" portfolios. Table 10 examines the possibility that overreaction or underreaction is driving the results presented in Section 1.5. Vasquez (2015) finds limited evidence suggesting that overreaction can explain some of the returns to a trading strategy involving one month straddles held for a week long period.

We examine the ability of our overreaction measure to account for returns to the straddle portfolio strategy described in Table 7. We focus only on the short term and long maturity straddle portfolios since these are where we see the largest and most significant returns. For the long maturity straddles, we use only the six month straddles. For the short maturity straddles we examine both one month and two month straddle portfolios. We look at both because the one month straddle portfolios potentially could be adulterated by events around option expiration. Since the two month straddles are sold with one month remaining on the straddles, this avoids any noise that could be attributed to erratic movements around expiration.

Panel A of Table 10 reports the results for one month options held to expiration. The coefficients on the underreaction as well as the overreaction factor returns are significant at the 1% level for most of the ten portfolios. We observe a trend in each of the coefficients across deciles. As one would expect, the loading on "underreaction" tends to be higher for the lower deciles and lower for the higher deciles. Conversely, there is a monotonic pattern in the "overreaction" coefficient. Loadings on the overreaction factor are increasing as we move from least inverted (Decile 1) to most inverted (Decile 10). In the final column of Panel A, we regress the 10-1 portfolio on the "overunder" factor. The alpha is significantly different from zero however, at -5.03%, its magnitude is about one third of the 10-1 straddle return of -14.41% reported in Table 7. This means that the traded "overunder" measure captures about two thirds of the returns associated with the one month straddle strategy based upon term structure slope.

In Panel B, we further investigate the relation between short maturity straddle returns and the overreaction measure, using two month options. Recall that the 10-1 returns for two month options described in Table 7 shows highly significant negative returns. The mean returns to the two month straddles are only 2.91% per month, not nearly as large as the one month straddle returns. In Panel B of Table 10, we see the same general pattern as described in Panel A. The most important difference however is that when we control for the "overunder" factor, the returns to the 10-1 portfolio are no longer statistically significant for the two month straddles. The intercept or the point estimate for unexplained returns are actually positive but insignificant at 0.21% per month. This further suggests that a large part of the returns we described in Table 7 for the short maturity options can be attributed to the measure of overreaction.

Panel C of Table 10 shows the results when portfolios of our six month straddles are regressed on the over and underreaction factors and the long-short portfolio is regressed on the overreaction minus underreaction factor. Although the loadings on each of these factors are not monotonic across the deciles, there is a general pattern of increasing sensitivity to the overreaction measure and a decreasing sensitivity to the underreaction factor as term structure becomes more inverted. When we regress the long-short portfolio on the "overunder" factor, the intercept remains highly significant and the magnitude actually increases from the returns reported in Table 7: from 2.62% to 3.37% per month.

The results of Table 10 suggest that a large portion of the returns to the short maturity straddle portfolio strategy based upon term structure slope can be attributed to a measure of overreaction documented by Goyal and Saretto (2009). For the one month straddles, about two thirds of the returns to the 10-1 Portfolio can be attributed to the overreaction factor but the unexplained returns are still significant. When we use two month straddles as our short maturity options in order to avoid calculating returns near expiration, we find that the returns unexplained by the overreaction factor are no longer significant. On the other hand, when we examine the long maturity straddles held for the same one month holding period, the overreaction factor cannot explain the returns shown in Table 7.

1.6 Robustness Checks

The analysis above supports the framework presented in Section 1.4. Here we examine the extent to which transactions costs, delta hedging, and upcoming earnings announcements affect our findings. Table 11 holds the time series average of the portfolio averages of firm size and the notional value of the firm's options contracts traded. The average size across term structure deciles is roughly constant, and the notional average option volume traded exhibits no pattern across deciles, but Decile 1 has the highest notional average dollar volume and Decile 10, the portfolio which produces the largest return differential across the term structure, has the lowest. In our calculations, the tables above have calculated returns using the midpoint of the bid-ask spreads for all options. Since Decile 10 is comprised of firms whose options are lightly traded, it is possible that transactions costs can explain the returns. In addition to being lightly traded, Table 12, which contains the options spreads sorted by maturity and decile, show that the options held in Decile 10 have relatively wide bid-ask spreads.

Table 13 examines the impact of transactions costs on Decile 10 returns. The one and six month Decile 10 portfolios, and the six month - one month calendar spread, are sorted into three buckets based on the bid-ask spread. Bucket 1 (3) holds options with a narrow (wide) spread. Since transactions costs are incorporated, the returns presented are consistent with the framework above: the one month portfolio holds short options positions and the six month portfolio holds long options. The six month-one month calendar spread holds long six month options and short one month options. The first column displays returns as if they were executed at the midpoint of the bid-ask spread. In this respect, the returns are calculated as they are in Section 1.5, and all returns are positive and significant, although they increase from Bucket 1 to 3. Columns two and three impose transactions costs. The returns in column two assume a 50% effective spread;[12] column three imposes a 100% effective spread where the full bid-ask spread is crossed. The narrowest spread bucket produces positive significant returns for the short one month options and the calendar spreads. Imposing a 50% (100%) calendar spread produces 9.66% (7.78%) monthly and a 1.47 (0.80) Sharpe Ratio. The second spread bucket manages to produce significant one month returns for the 50% effective spread, generating a significant 4.99% monthly return and a 0.75 Sharpe Ratio. The portfolios with the widest bid-ask spreads find that returns deteriorate when incorporating transactions costs as the calendar spread returns are negative. The return dynamics persist when incorporating bid-ask spreads if options with relatively narrow bid-ask spreads are held. However, since Decile 10 holds options with lower trading volume, limits may exist to capturing these return differentials.

In explaining the interaction between term structure and volatility dynamics, our framework centers on a term structure inversion witnessed in Decile 10, as the short term implied volatility elevates in anticipation of an impending shock. Until here, returns have been calculated by entering options positions and exiting them

[12]As an example, if the spread is $1.00 at $2.00, a 50% effective spread is $1.25 at $1.75. The purchase price here would be $1.75.

once the holding period ends. Table 14 examines whether the shock is manifested in daily price movements in the underlying equity by delta hedging the options daily. Return calculations follow the procedures set forth in Frazzini and Pedersen (2012). At trade inception, straddles worth \$1 worth are held, $V_0 = 1$. Each day, the value of the portfolio is computed iteratively as follows:

$$V_t = V_{t-1} + x(F_t - F_{t-1}) - x\Delta_{t-1} r_t^S S_{t-1} + r_t^f (V_{t-1} - xF_{t-1} + x\Delta_{t-1} S_{t-1}) \quad (1.6)$$

where $x = 1/F_0$, the number of options contracts; F is the option price; r^s is the daily stock return; r^f is the daily risk free rate; and Δ is the option's delta. The second term above represents the dollar return from the change in option price, the profit or loss from the delta hedge is computed in the third term. The final term calculates the financing cost of the position. The return to the position, R_T, is

$$R_T = V_T - V_0 = V_T - 1 \quad (1.7)$$

The return patterns when delta hedging the options position mirror those from Table 7. For one month options, the returns drop monotonically from 3.68% to -7.30% from Decile 1 to Decile 10. The same occurs for the two month returns, although the difference is smaller in magnitude. The 10-1 Portfolio, which owns Decile 10 and shorts Decile 1, turns positive with three month options here, one month earlier seen in Table 7, and is significantly positive for four through six month options. Incorporating daily price movements do not materially impact the return dynamics of options portfolios across the term structure.

Finally, it is possible that the returns from term structure inversions are driven by known upcoming events. Table 15 holds the one, two, and six month option returns, separated by whether the firm has an earnings release scheduled in the next options expiration cycle. Interestingly, in the subsample where earnings releases are upcoming, the returns for one month options, those with the highest exposure to moves in the underlying stock, are *higher* than when there is no upcoming earnings release. For Deciles 1 through 3, the returns are positive and significant, from 18.44% to 9.52%, compared to 1.07% to -2.65% for the sample without an upcoming earnings release. In either subsample, the patterns persist: returns decrease from Decile 1 to Decile 10 for the one and two month options, increase for the six month options, and the 10-1 Portfolio returns are significant. Either sample supports our framework.

1.7 Conclusion

We examine the term structure of volatility in the cross-section of equity options to reveal several novel facts. We show that term structure of volatility among individual stocks behaves differently from that of the index. In the cross-section we find that movements in the term structure are driven by changes in short term volatility, and unlike in the index, the premia associated with volatility is strongly dependent upon *both* horizon and slope of the volatility term structure. We show that long term implied volatility is slow to react to these shocks in short term implied volatility. Furthermore, the speed with which long term volatility reacts to shocks depends upon the slope of the implied volatility curve. We propose a simplified framework for understanding our empirical findings. Based upon our analysis and proposed framework, we propose strategies for trading ATM option straddles across maturities. The returns to these trading strategies perform consistent with the volatility term structure dynamics and the predictions of our framework. We find that the profitability of our strategies in long maturity straddles are driven by an interaction between the term structure and realized volatility. On the other hand, short maturity straddle returns appear not to be be driven by this type of interaction.

While the literature studying index options is much larger than that of options on individual equities, the number of studies empirically examining the cross-section of individual equity options has rapidly grown in recent years. The vast majority of papers studying the cross-section of individual options examine only those options with a fixed, single month to maturity. A number of option pricing anomalies have been uncovered in the cross-section of these options. Often, these anomalies are not existent in index options. This highlights the need for empirical research in the cross-section of individual options *in addition to* the empirical work studying index options. Our results provide a new and important way of understanding option prices in the cross-section. We contribute to the literature by studying the dynamics of options prices across maturities and term structure. This allows us to uncover new empirical facts about the relative pricing of options across maturities, a dimension that has until now been unexplored in the literature.

CHAPTER 2

VOLATILITY CARRY

2.1 Introduction

Asset managers have employed the carry trade for decades in foreign exchange. The strategy, in which investors buy (sell) currency pairs forward when the forward rate is at a discount (premium) to the current spot rate, has consistently produced significant risk-adjusted returns.[1] Carry owes its returns to the violation of the uncovered interest parity (UIP) hypothesis; Hansen and Hodrick (1980) and Fama (1984) showed that forward foreign exchange rates are biased indicators of future spot levels.[2] The strategy has been studied extensively and has been found to be positively exposed to crash risk, liquidity risk, volatility risk, and peso problems.[3] Across asset classes, the term structure of prices is central to the analysis of carry, as the trade centers on the difference between spot and forward price,[4] and carry has been applied more generally to show that the returns to carry permeate across assets: forward asset prices are poor predictors of future spot asset prices, significant returns to carry exist, and as in foreign exchange, the returns across asset classes generally are exposed to liquidity, volatility, and

[1]See, for example, Jurek (2014).

[2]Also see Meese and Rogoff (1983) for an early examination of carry in the foreign exchange market.

[3]See Farhi and Gabaix (2015) for crash risk; Brunnermeier, Nagel, and Pedersen (2008) for liquidity risk; Burnside, Eichenbaum, Kleshchelski, and Rebelo (2010) for peso problems; Menkhoff, Sarno, Schmeling, and Schrimpf (2012) and Lustig, Roussanov, and Verdelhan (2011) for volatility risk.

[4]Related studies to carry in other asset classes center on the basis in commodities, see Gorton, Hayashi, and Rouwenhorst (2013) and Yang (2013); and slope in bonds, see Fama and Bliss (1987) and Campbell and Shiller (1991).

macroeconomic factors.[5] This analysis of term structure has been applied to index options and volatility: Simon and Campasano (2014) and Johnson (2016) show that the slope of the implied volatility term structure predicts returns, and VIX futures prices are biased indicators of future spot levels of the VIX Index. Simon and Campasano (2014) show that a VIX futures trading strategy centered on the VIX basis produces positive returns, and Johnson (2016) shows that slope predicts the returns to index variance assets generally. Koijen, Moskowitz, Pedersen, and Vrugt (2013) find significantly positive returns when applying the concept to index option put and call prices. While these studies show that term structure slope informs returns and profitable carry strategies in index options and index implied volatility exist, Vasquez (2015) and Campasano and Linn (2017) show that the index and equity option volatility dynamics conditional on term structure differ. Index term structure slope is *negatively* related to variance returns across the term structure; however, Campasano and Linn (2017) demonstrate that equity option returns depend on an interaction between the slope of the term structure and the horizon of the options: for short-dated options, term structure slope has a *positive* relationship with equity option returns, for long-dated options, slope negatively impacts returns. Due to these differences, I investigate the concept of carry in the equity volatility market. I find that the strategy produces positive significant returns, as forward volatility is not predictive of future spot volatility. Unlike the returns to carry in other assets, however, I find that the equity implied volatility carry trade is not exposed to volatility or liquidity factors and loads negatively on the market. After accounting for transactions costs, a long volatility carry portfolio produces significantly positive returns and is negatively exposed to the market, challenging traditional theories of asset pricing.

Koijen, Moskowitz, Pedersen, and Vrugt (2013) broadly define carry as the returns to any futures or forward asset if the spot price remains the same, and examine the returns to carry in global equities and bonds, treasuries, commodities,

[5]See Koijen, Moskowitz, Pedersen, and Vrugt (2013).

credit, and index options. Their application to index options centers on the option prices, and is affected by the impact of time decay and the path of the underlying. My analysis is more closely related to Simon and Campasano (2014) and Johnson (2016) and the Della Corte, Sarno, and Tsiakas (2011) and Della Corte, Kozhan, and Neuberger (2016) studies. Della Corte, Sarno, and Tsiakas (2011) use forward volatility agreements (FVA), an over-the-counter swap, to show that a volatility carry strategy in foreign exchange produces significant returns by buying (selling) FVAs when the level is lower (higher) than the current spot implied volatility. In the equity options market, while FVAs and forward variance swaps rarely are traded, they can be replicated from equity option prices by following Britten-Jones and Neuberger (2000). Since variance swaps are more commonly traded in the index market, I choose to synthesize forward variance swap rates. By comparing the forward and spot variance rates, I form portfolios each month. I show that the forward variance rate is a biased predictor of the future spot variance rate when the current and forward variance rates diverge, and find that a long/short portfolio which buys (sells) forward variance when less (greater) than the current spot produces significant returns. While variance swaps and forward variance swaps are replicated using the prices of listed equity options, the rates calculated are hypothetical and do not represent the rates of swaps actually traded. I examine an investable version of the carry trade by employing an options structure known as a calendar, or time spread, and find that a long/short portfolio also produce significant returns. I then examine the extent to which stock liquidity, upcoming earnings releases, and maturity impact the returns to equity volatility carry. I find that, although exposed to both stock liquidity and maturity, neither completely account for the returns. These findings, along with the absence of or negative loading on market factors, are supportive of the Campasano and Linn (2017) framework and the Garleanu, Pedersen, and Poteshman (2009) model of demand-based pricing and help inform the difference between the returns to equity volatility carry and other assets, including index volatility. The Campasano and Linn (2017) framework illustrates how positive returns to a long equity volatility carry would arise; similarly, the demand based options pricing theory of Garleanu, Pedersen, and Poteshman (2009) is consistent with these returns to carry. The theory holds that price sensitivity is proportional to the unhedgeable risk of that asset. One measure of unhedgeability cited by Garleanu, Pedersen, and Poteshman (2009) is the gamma, or the change of an option's delta with respect to the underlying. Since gamma and horizon are negatively related, it directly affects the pricing of short maturity forward variance and calendar spreads. This is consistent with my findings that higher returns to carry are found in shorter maturities and in less liquid stocks.

The following section describes how I apply the concept to the equity volatility market. Section 2.3 discusses the data and methodology employed. Section 2.4 reviews the implementation of the carry strategy. Section 2.5 examines the exposure to state variables and the returns to carry in other assets; Section 2.6 concludes this chapter.

2.2 Volatility Carry

In applying carry to the equity volatility market, the definition, construction, and execution differs somewhat from other markets. I discuss how it is implemented here as well as the issues which arise peculiar to the options market.

Koijen, Moskowitz, Pedersen, and Vrugt (2013) define carry generally as a "futures (or synthetic futures if none exist) return assuming prices stay the same." Thus, the carry is the difference between the futures or forward price and the spot price for any asset. In the foreign currency market, carry trades are constructed where currency pairs are bought (sold) forward when the forward rate is less (greater) than the current spot rate. In the foreign exchange implied volatility market, the carry trade may be effected through the use of an over-the-counter swap known as a forward volatility agreement (FVA). Della Corte, Sarno, and Tsiakas (2011) and Della Corte, Kozhan, and Neuberger (2016) show that the foreign exchange volatility carry trade produces significant returns by buying (selling) forward implied volatility when the forward level is less (greater) than the current spot level of implied volatility, and these returns strategy cannot be explained by foreign exchange carry trade returns.

In the equity index volatility market, forward variance swaps (FV) are more commonly traded than FVAs, and in individual equities, neither are commonly traded. While FVA prices can be synthesized, I choose to synthesize forward variance swaps since they are more commonly traded in the equity markets. As with FVAs, the maturities and forward periods can be varied. Assuming that the period in question begins at τ_1 and ends at τ_2, then the buyer of $FV(\tau_1, \tau_2 - \tau_1)$ exchanges the $\tau_2 - \tau_1$ month variance swap at τ_1 at a level agreed upon today for the $\tau_2 - \tau_1$ variance swap (VS) determined at τ_1, $VS_{\tau_1}(\tau_2 - \tau_1)$. The payoff to owning this forward variance swap equals

$$(VS_{\tau_1}(\tau_2 - \tau_1) - FV(\tau_1, \tau_2)) * V \tag{2.1}$$

where V is the notional implied variance traded. In effecting a carry trade in equity volatility, then, the forward implied variance level is compared to the current spot implied variance level. If the forward implied variance level is less (greater) than the current spot implied variance rate, the forward variance swap is bought (sold).

In order to synthesize the forward variance levels, I first calculate two variance swap rates: $VS_t(\tau_2 - \tau_0)$ and $VS_t(\tau_1 - \tau_0)$ by following the procedure from Carr and Wu (2009).[6] With the two variance swap levels, I then calculate the forward variance swap rate. Since variance is additive,

$$VS_{\tau_0}(\tau_2 - \tau_0) = VS_{\tau_0}(\tau_1 - \tau_0) + VS_{\tau_1}(\tau_2 - \tau_1). \tag{2.2}$$

[6] Carr and Wu (2009) synthesizes equity variance swaps following Carr and Madan (1998) and Britten-Jones and Neuberger (2000), who show that under certain assumptions the model-free implied variance can be calculated from a set of options prices. Jiang and Tian (2005) relaxes these assumptions to allow for jumps in the underlying.

Substituting $FV(t_1, t_2)$ for $VS_{\tau_1}(\tau_2 - \tau_1)$, simple manipulation of equation 2.2 yields:

$$FV(t_1, t_2) = VS(\tau_2 - \tau_0) - VS(\tau_1 - \tau_0). \tag{2.3}$$

From Equation 2.3, I synthesize forward variance swaps using the two variance swap rates by subtracting the short maturity swap, $VS(\tau_1 - \tau_0)$ from the long maturity swap $VS(\tau_2 - \tau_0)$. Revisiting Equation 2.1, the payoff to the swap equals the difference between the forward and future spot variance levels, and the returns to the forward variance swap can be determined as a function of the forward variance swap level:

$$r_{FV} = \frac{VS_{\tau_1}(\tau_2 - \tau_1)}{FV(t_1, t_2)} - 1. \tag{2.4}$$

The following serves as an example of the calculation of the forward variance swap rate and return. On April 20, 2015, the one and two month variance swap levels for Chipotle Mexican Grill (CMG) are 1352.58 and 778.74, and the days until expiration for each are 25 and 60 days, respectively. The FV(1,1) level is calculated by subtracting the one month level from the two month level, after adjusting for the number of days until expiration:

$$FV(1,1) = \frac{(778.74 * 60) - (1532.58 * 25)}{60 - 25} = 368.86$$

At the one month expiration date, May 15, 2015, the one month variance swap level is 292.55, and the return to the forward variance swap is $\frac{292.55}{368.86} - 1 = -20.69\%$. Note that the returns to a forward variance swap are derived from implied variance levels only, while the returns to a variance swap are determined using the implied variance level and the variance realized by the underlying over the period identified. Thus, the analysis here differs from option studies which examine the difference between the volatility realized by the underlying and the option implied volatility, or the difference between the value of options at entry and expiration, which incorporate the movement of the underlying.[7]

Since the levels are synthesized and do not represent the rates from actual swaps, I also examine an investable version of the carry trade. Forward variance swap prices are determined by incorporating the prices of all valid options from the short and long maturities, and is calculated by subtracting a short maturity variance swap level from a long maturity variance swap level. The investable version takes the form of a calendar spread, with equal notional sizes of ATM short and long maturity straddles where one buys a long maturity ATM straddle and sells a short maturity ATM straddle.[8] This position has zero delta and no directional exposure at inception, but path dependency when employing vanilla options is unavoidable, and the returns of calendar spreads will suffer if the price of the underlying moves away from the strike. As this may negatively impact returns, it serves to understate the returns relative to those of the forward variance structure.

2.3 Data and Methodology

The OptionMetrics Ivy Database is the source for all equity options prices, equity prices, and risk-free rates. In addition, I use the deltas and implied volatilities (IVs) supplied by OptionMetrics in forming the portfolios, following the literature. The dataset includes U.S. equity options from January, 1996, through August, 2015 with one and two month maturities. I apply the standard filters and discard any options which have no bid price or violate arbitrage conditions. I also require the underlying equity price to be greater than $10. When constructing variance swaps, I require a minimum of two valid OTM put and call options for both one and two month maturities, following the procedure set forth in Carr and Wu (2009).[9] The day following each standard monthly expiration, I calculate variance

[7] For example, see Coval and Shumway (2001), Bakshi and Kapadia (2003a), Bakshi and Kapadia (2003b), Carr and Wu (2009), Goyal and Saretto (2009), Cao and Han (2013), among others.

[8] Unpublished alternative implementations yield similar results.

[9] I relax the requirement in Carr and Wu (2009) here from three options to two to be more inclusive, as Carr and Wu (2009) uses 35 equities with the most liquid options.

and forward variance swap prices and form portfolios.[10] Using the IVs of eligible options, I create a grid of 1000 option prices between moneyness levels of 0.01% to 300%, and interpolate the implied volatilities for the options using a cubic spline. For the moneyness levels outside the lowest and highest strikes observed, I flatten the surface based on the implied volatilities of the lowest and highest observed strikes. I calculate OTM option prices for the 1000 options using the implied volatilities and then the variance swap rate, again following Carr and Wu (2009). Specifically,

$$V(t,\tau) \approx \int_{S(t)}^{\infty} \frac{2}{K^2} C(t,\tau,K)dK + \int_{0}^{S(t)} \frac{2}{K^2} P(t,\tau,K)dK \tag{2.5}$$

where V represents the implied variance; C and P the call and put prices; and K the strike price.[11] Once I have the one and two month variance swap levels, I calculate the $FV(1,1)$ rate using one and two month variance swap levels, and then sort into ten portfolios based on the percentage difference between the forward and current spot variance level, with Portfolio 1 (10) holding positions where the forward level is highest (lowest) relative to the spot level. The sample period includes 56,932 variance swaps and 2,977 equities.

Variance swaps avoid the path dependency issues inherent in vanilla options strategies, and index variance swaps have been examined recently by Aıt-Sahalia, Karaman, and Mancini (2014) and Dew-Becker, Giglio, Le, and Rodriguez (2015). However, they are rarely traded on all but the most liquid equities, and so I use ATM equity options to examine investable strategies. Instead of using two and one month variance swap levels to determine the forward variance level, the structure, a calendar spread, consists of a long two month, short one month ATM straddle, held in notionally equal amounts. Since a straddle consists of one put and call option, I relax the filter above to require only one valid OTM put and call

[10] Standard procedure in the literature, and that which I follow when calculating the returns of investable portfolios, forms portfolios on the day following expiration, and the entry prices the day after that. I calculate opening prices and form portfolios on the same day because when I delay the determination of entry prices, my sample size drops by approximately 25%.

[11] In the calculation, I include the approximation error for jumps in the underlying process.

option for each expiry. Portfolio formation and construction for calendar spreads follow procedure set forth by Goyal and Saretto (2009). The day following the standard monthly expiration, typically a Monday, eligible options are identified, structures are created, and portfolios sorted on the difference between forward and spot volatility. While portfolios are formed the day following expiration (Monday), the opening prices used when calculating options returns are taken the following day (Tuesday), in order to avoid any microstructure issues which may arise from forming and trading the portfolios on the same day. The positions are held until the one month options expire, where at that time the two month options are sold. For both entry and exit prices, the midpoint between the bid and ask prices is used. The returns to the structure equal $\frac{CS_{t+1}}{CS_t} - 1$, where CS_t equals the price of the two month minus the one month ATM straddles; CS_{t+1} equals the price of the two month straddle on the following expiration minus the expiration value of the one month ATM straddles. The relaxed data filters here yield a larger sample than for the forward variance swaps: 284,984 spreads on 6,799 equities.

2.4 Returns to Volatility Carry

2.4.1 Carry: Forward Variance Swaps

To begin I sort each month on the percentage difference between the spot and forward variance rates and form ten portfolios. This comparison of spot and forward variance is directly analogous to the implementation of carry in foreign exchange and other markets. Table 16 contains the time series averages and first differences of the one and two month variance swap levels, $VS(1)$ and $VS(2)$, and the one month forward one month variance swap level, $FV(1,1)$ for the ten portfolios and the entire sample. While variance swaps are more commonly traded than volatility swaps, I also include the time series averages for model free implied volatility (MFIV).[12] Since traded variance and volatility swaps are expressed in

[12] $MFIV = \sqrt{V} or \sqrt{FV}$, from equations 1 and 3, respectively.

volatility or variance"points", I do so here. The first row shows the deviation of forward from spot variance, and is the measure on which portfolios are formed; Decile 1 (10) contains firms whose spot variance is lower (higher) than forward. From Equation 2.3, the forward variance level is equal to the difference between the longer and shorter dated variance swap, adjusted for the maturities of each, and so is directly dependent on the slope of the term structure of implied volatility. The one and two month variance swap levels across portfolios illustrate how shifts in the term structure are driven by the one month maturity. While the $VS(2)$ level stays fairly constant across portfolios, the $VS(1)$ rate is monotonically increasing from Decile 1 to 10. As $VS(1)$ increases from 2753.84 to 4818.16 and $VS(2)$ remains constant, the forward rate drops. In Decile 1, $FV(1,1)$, at 4049.92, sits above the $V(1)$ rate of 2753.84. In Decile 10, the $V(1)$ is almost double the $FV(1,1)$ level (4848.16 vs. 2763.87). Figure 4 graphically depicts the relationship between current one month variance swap and FV(1,1) levels.

The first differences listed in Table 16 confirm that the short maturity implied volatility drives changes in the term structure, and thus changes in the forward variance level. Each month when portfolios are formed I compute the one and two month implied variances for each equity for the month prior, and average them. The first differences for $VS(1)$ and $VS(2)$ are the time series averages of these cross-sectional means. While the two month variance swap level for Decile 1 increases by more than the one month level decreases, 14.23% vs. -10.96%, the changes in Decile 9 and 10 show that the volatility term structure from the preceding month has steepened. The two month levels increase by 1.48 and 8.10% while the one month VS rates increase by 14.56 and 40.63% respectively. Term structure inversion and the difference between spot and forward variance is driven by the relative increase of the short term rate.

Two landmark studies of the carry trade, Bilson (1981) and Fama (1984), begin with an examination of an expectations hypothesis, or "speculative efficiency hypothesis", which holds that forward rates are unbiased predictors of future spot rates. To test the hypothesis here, I run the analogue of the Bilson (1981) and Fama (1984) predictive regressions. Using the time series averages of the ten portfolios created, I regress the one month implied variance of period t+1 on the current forward volatility:

$$VS_{t+1}(1) = \alpha + \beta * FV(1,1) + \epsilon_{t+1} \tag{2.6}$$

If the speculative efficiency hypothesis holds, then $\alpha = 0$ and $\beta = 1$. Table 17 holds the results to these regressions. In eight of the ten portfolios, α is not statistically different from 0. The estimates of β increase monotonically from Deciles 1 to 10. For the first two deciles, the hypothesis $\beta = 1$ is violated at the 1% level as the estimates are 0.8612 and 0.8861. For Deciles 8 through 10, the estimates for β are significantly greater than one, violating the null at the 1% level. An estimate of β less (greater) than one indicates that the forward variance level overstates (understates) the future spot variance rate. As portfolios are created by sorting on the difference between current spot variance and forward variance, when the two diverge in Deciles 1, 2, 8, 9 and 10, the volatility analogue of the speculative efficiency hypothesis is violated. When the forward variance level is greater than the spot rate in Deciles 1 and 2, the forward rate serves to overstate future spot variance; when the forward variance level is less than the spot rate in Deciles 8 through 10, the forward rate understates future spot variance. At the extremes, however, the forward variance level appears to predict changes in variance swap levels: Figure 5 displays the FV(1,1) levels along with the current and t+1 one month variance swap levels.

If the forward variance rate is a biased predictor of future spot rates, then a trading strategy can be crafted to exploit this bias. Table 18 directly examines the implied volatility carry trade, holding the return statistics for the ten equally weighted portfolios of forward variance swaps, where returns are calculated as $\frac{VS_{t+1}(1)}{FV(1,1)} - 1$. The returns here increase monotonically from Decile 1 to 10. The first portfolio yields losses significantly different than zero, losing 5.557% per month.

From Deciles 4 through 10, the returns are positive and statistically significant, reaching 19.67 and 49.68% in Deciles 9 and 10 respectively. The return volatility remains fairly constant from Deciles 1 to 8, ranging from 27.54% to 36.84%, before rising to 41.68% and 114.33 % in the last two portfolios. The 10-1 long/short portfolio, earning 55.25% each month with a volatility of 103.33%, produces an annualized Sharpe Ratio of 1.85.

2.4.2 Carry: Calendar Spreads

Since the variance swap rates are hypothetical, I look at an investable version of carry using ATM straddles. Recall from Equation 2.3 that the forward variance swap levels are determined by subtracting the one month from the two month VS level, adjusted for the relative maturities. From Britten-Jones and Neuberger (2000), the variance swap levels are derived from a set of options prices for each expiration date. The investable trade structure, a calendar spread, requires only one ATM put and call for the one and two month maturities, and buys the two month ATM straddle and sells the one month ATM straddle. By requiring an equal number of options at each maturity, the structure has a pre-defined maximum loss, similar to both a long option position and the forward variance swap. Since two ATM straddles are used, the position will have no delta at inception, but the payoff of this structure is dependent on the path of the underlying, unlike that of the variance swap. This dynamic, however, will serve to lower returns if the underlying moves from the strike price, and so will cause returns from the calendar spread to be lower than that of the variance swap if the underlying price moves away from the strike prices. The following comparison serves as an example of the impact of the underlying movement. On April 21, 2015, with the stock price of Chipotle Mexican Grill at \$692.52, the two month 690 straddle price is \$64.50, the one month 690 straddle price is \$56.20, and the one month - two month calendar spread costs \$8.30. On May 15, 2015, the one month straddle expires with the stock price at \$632.37. The value of the one month straddle at expiration, the absolute difference between the strike and the stock price, is \$57.63. The value of the long-dated straddle (now a one month straddle), is \$58.875, and thus the closing price of the calendar spread is \$1.245, resulting in a loss of 85.06%. By comparison, the hypothetical one month forward one month variance swap rate for Chipotle Mexican Grill in April, 2015, is 3680, and the closing price, the one month variance swap rate in May, is 2930, resulting in a loss of 20.69%.

The day after each standard monthly expiration, I identify eligible equities and sort into portfolios based on the implied volatility of the one month ATM straddle and the one month ATM volatility level one month forward, as calculated above.[13] This sort is directly analogous to the portfolio sorting method in Table 16. Table 19 holds the summary statistics for the calendar spreads. The first row, $\frac{1mIV}{FV(1,1)} - 1$, holds the difference between the spot and forward ATM implied volatility. The extreme portfolios' volatility differential is comparable to that of the variance swaps. The one month IV stands 20.38% less than the one month forward IV for Decile 1, compared to 18.78% for the variance swaps; for Decile 10, the one month IV stands 41.57% higher, while the difference is 35.24% for that of the variance swap portfolio. As with the variance swaps, the two month ATM implied volatility is fairly constant, varying less than three percentage points, while the one month implied volatility ranges from 0.3928 to 0.5289. The straddles are closest to at the money, but have some residual data: Table 19 shows that the average deltas are less than 1% (from 0.30% to 0.76%).

Table 20 holds the returns of the one and two month straddle returns and the calendar spread returns. The calendar spread returns, as with those of the forward variance swaps, increase monotonically from Decile 1 to 10. Similar to the forward variance swap, all portfolios post significantly positive returns (for the forward variance swaps, nine of the ten portfolio returns are positive). Consistent with the volatility dynamics from Tables 16 and 19, the two month straddle returns

[13]While classifying this as forward volatility is an abuse of notation, it remains consistent with the forward variance swap analysis. And, since the forward level is calculated from the one and two month straddles, a sort on one and two month IV differential is equivalent.

are constant across portfolios; the calendar spread returns are driven by the one month straddle, as they decrease from -3.69% to -13.90%. The calendar spread portfolio for Decile 10 produces an average monthly return of 52.77% with a Sharpe Ratio of 7.05, and the 10-1 Long/Short Portfolio shows arbitrage-like profits, with an annualized Sharpe Ratio of 7.12. Figure 6 plots the returns of the carry trade employing forward variance swaps, calendar spreads, and the returns of the S&P 500 Index. The variance swap and calendar spread portfolios are scaled so that 1% is invested each month since both portfolio have higher volatilities than the market. Both variations of the carry trade appear profitable during the dot-com bubble burst and the financial crisis.

Since the midpoint of the bid-ask spread is used for the entry prices, and the long maturity straddle also is exited at the midpoint between the bid and ask prices, transactions costs could eclipse the profits. Table 21 sorts the calendar spread returns from Table 20 by the bid-ask spread as a percentage of the option prices. Spread Quintile 1 (5) holds the time-series averages of five portfolios with the narrowest (widest) bid-ask spread. The returns are then calculated applying a 50% effective bid-ask spread for the entries and the exit of the two month straddle. Including transactions costs renders Spread Quintiles 2 through 5 unprofitable or insignificantly profitable; for Spread Quintile 1, the Long/Short 5-1 Portfolio posts negative returns. As this is a long/short portfolio of calendar spreads, however, a total of six bid-ask spreads must be crossed: At inception, each spread holds a one and two month ATM straddle the bid-ask spreads of which must be crossed; at exit, the bid-ask spread of the two month straddle must be crossed. The returns of the 10-1 Portfolio are driven by Decile 10, however: and, in Spread Quintile 1, Slope Portfolios 4 and 5 survive the effects of imposing transactions costs and produce significantly positive returns; Slope Quintile 5 returns 9.65% monthly with a 1.39 Sharpe Ratio. Again, referring back to Table 20 calculated using the midpoints, the returns to the Deciles 9 and 10 portfolios dwarf the Decile 1 returns. Decile 1 posts a 4.25% profit with 13.30% return volatility, while Deciles

9 and 10 produce returns of 31.35% and 52.77% with return volatilities less than double that of Decile 1. The Sharpe Ratios of Deciles 9 and 10, 5.13 and 7.05, illustrate that the returns to equity volatility carry are driven by inverted volatility term structure: buying variance forward, or buying the calendar spreads, produce large returns when the curve is most inverted; when applying transactions costs, these returns survive. Figure 7 plots the returns of the Spread Quintile 1, Slope Quintile 5 Portfolio and the S&P 500 Index. As with the long-short variance swap and calendar spread portfolios, the Decile 10 returns increase during the financial crisis and the post-Internet bubble period.

The summary statistics of both the forward variance swaps and the calendar spreads are right skewed. The current variance swap rate for Decile 1 is roughly 33% lower than the forward rate, while for Decile 10 the current rate is almost double that of the forward variance swap rate. In sympathy, the one month implied volatility of the ATM straddle is 20% less than that of the one month implied volatility one month forward, while the one month implied volatility for Decile 10 is more than 40% higher than the forward ATM IV. Since forward volatility is a function of the relationship between the one and two month IV, and the two month IVs are fairly constant across deciles, a relatively elevated one month IV produces the comparatively low forward volatilities for Deciles 8 through 10. As the forward implied volatility level is driven by the one month maturity, so are the returns: the two month straddle and variance swap returns in Tables 18 and 20 are roughly constant, and the one month returns decrease from Deciles 1 to 10. Since the forward variance swap and calendar spread returns can be decomposed into a long two month, short one month position, the significant returns for Slope Quintiles 4 and 5 in Table 21 are a function of the relatively low returns of the one month positions.

Vasquez (2015) shows that term structure and short maturity option returns have a negative relationship, and Campasano and Linn (2017) show that the return dynamics for short maturity equity and index options differ when conditioning on term structure slope. Campasano and Linn (2017) also illustrate that equity option returns conditional on implied volatility term structure are dependent on an interaction between term structure slope and maturity. While term structure slope and short maturity equity option returns have a negative relationship, slope and long maturity equity option returns have a *positive* relationship. This interaction between slope and maturity is not present in index options.[14] Campasano and Linn (2017) describe a very simple framework in seeking to explain this interaction. In anticipation of a shock, the term structure slope inverts due to an increase in short maturity implied volatility, since these options are more sensitive to the movement of the underlying asset. If the shock transpires, the gains to short maturity options are muted due to the anticipatory movement in implied volatility. If, however, the shock does not occur, the losses to short maturity options will be relatively large. In contrast, long maturity option implied volatility does not adjust to the shock *ex ante*. If the shock does not occur, the impact to long maturity option returns is muted; however, if the shock occurs, the long maturity implied volatility will increase, producing positive returns. This framework is supportive of the Garleanu, Pedersen, and Poteshman (2009) demand-based model of option pricing, which shows that demand pressure increases option prices in proportion to the unhedgeable part of the option, and also impacts other options in proportion to the covariance of their unhedgeability. Two of the three unhedgeable risks examined in Garleanu, Pedersen, and Poteshman (2009), jumps in the underlying asset and discrete-time hedging, more heavily impact short maturity options due to the negative relationship between an option's maturity and its gamma, the sensitivity of a delta hedged option return to a move in the underlying. The following section examines the effects upcoming earnings releases, equity volume and market capitalization have on the returns to carry. I use equity volume and market capitalization as a proxy for stock liquidity, as a less liquid underlying could exacerbate the costs of discrete time hedging. Earnings releases may re-

[14] See Johnson (2016).

sult in discontinuities and in anticipation of the release produce a inverted implied volatility term structure slope; I divide the sample to see whether earnings account for the returns to carry. Finally, I examine the returns to deferred carry positions to gauge the extent to which maturity impacts returns. As maturity increases, gamma decreases, and the returns to carry should drop as the effects described in Campasano and Linn (2017) and Garleanu, Pedersen, and Poteshman (2009) will be muted.

2.5 Examination of Carry Returns

2.5.1 Earnings Releases

Each month, I identify the firms with earnings announcements scheduled to be held before the one month options expiration.[15] I perform two sorts on the calendar spread returns: the first divides the sample according to whether an upcoming earning announcement is scheduled, the second sorts into quintiles based on term structure slope. Figure 8 displays the average percentage composition of each portfolio of firms with and without an earnings release over the next expiration cycle. The percentage of the portfolio comprised of firms with an upcoming earnings announcement increases from Quintile 1 (16.7%) to Quintile 5 (43.7%). Since the release may impact the underlying equity price, short-term implied volatility shifts higher due to the negative relationship between maturity and gamma, lowering the implied volatility term structure slope. Table 22 holds the results for the two sub-samples with and without an upcoming earnings release. The return pattern for both monotonically increase across slope quintiles for both groups, and the long-short carry portfolio of firms without an earnings announcement produce higher returns than the portfolio of firms with an earnings announcement: a portfolio which owns the 5-1 portfolio for those firms with an upcoming earnings release and shorts the 5-1 portfolio without a release loses 9.72% monthly with a

[15] Earnings release information is obtained from the Compustat database.

Sharpe Ratio of -0.79. While scheduled earnings releases may impact the slope of the implied volatility term structure, it does not account for the returns to carry.

2.5.2 Equity Volume

Garleanu, Pedersen, and Poteshman (2009) cite discrete time hedging as an unhedgeable risk. Since continuously hedging an option position is difficult to accomplish in practice, the movement of the underlying between the time at which the option is hedged is an open exposure which lessens as the time between hedging transactions decreases. Assuming that options investors are unable to continuously hedge and the time intervals between hedging transaction is constant across firms, the liquidity of the underlying may impact the effectiveness of the hedge, as hedging executed on less liquid firms may prove less effective due to higher transactions costs. Here, I examine the impact of equity volume and market capitalization on the carry returns, where volume and market capitalization act as proxies for stock liquidity. Each month, I sort the sample into quintiles based on the term structure slope and the prior month's average daily dollar volume traded as a percentage of the firm's market capitalization.[16] The long/short carry returns across the stock volume quintiles are fairly consistent, and the Sharpe Ratios for Volume Quintiles 1 through 4 is virtually unchanged, ranging from 4.28 to 4.48; for Volume Quintile 5 the Sharpe Ratio is lower at 4.02. To gauge the impact of volume on returns, I include a long/short portfolio which buys the 5-1 Portfolio for firms with the lowest volume and shorts the 5-1 Portfolio for firms with the highest. The low volume 5-1 Portfolio outperforms that of the high volume by 10.06% each month with a Sharpe Ratio of 0.89.

The second proxy for liquidity is market capitalization, the results of which are held in Table 24. As previously done, the calendar spreads are sorted on implied volatility term structure slope and then on the average size of the firm calculated in the prior month. The spread in returns and Sharpe Ratios for the

[16]Unreported sorts using a longer period in which to calculate the volume figure yield similar results.

5-1 portfolios across market capitalization is wider than that seen in the double sort on stock volume and slope in table 23. The Sharpe Ratio drops from 5.09 to 2.73 from Size Quintile 1 to 5; by comparison, the drop from Volume Quintile 1 to 5 is 4.48 to 4.02. A portfolio which owns the 5-1 Portfolio for small firms and sells the 5-1 Portfolio for large firms earns 14.57% monthly, with a 1.20 Sharpe Ratio. While the 5-1 returns are significant across firm size and market volume, a return differential exists between low and high volume and small and large firms.

2.5.3 Returns to Deferred Carry Portfolios

Until this point, the carry trades consist of one and two month positions. I next examine the returns to two month-four month and three month-six month calendar spreads.[17] Increasing both the forward period and maturity will decrease exposure to the effects of discrete time hedging and also mute the dynamics of the Campasano and Linn (2017) framework. Table 25 holds the returns of both deferred carry trades, sorted into term structure slope deciles. As with the one month-two month calendar spreads, returns increase monotonically for both from Decile 1 to 10, and returns are significant across deciles. However, the Sharpe Ratios of the long-short portfolios decrease as maturities increase. Recall from Table 20 the Sharpe Ratio of 7.12 for the one month-two month calendar spread. The ratio more than halves, to 3.16, for the two month-four month calendar spread, and decreases further to 2.65 for the three month-six month calendar spread. As with volume and size, the deferred carry positions remain profitable; however, the risk-adjusted returns decline.

[17]Given the equity option listing conventions, the number of observations for both deferred spreads are lower. For a more detailed explanation of listing conventions, see Campasano and Linn (2017).

2.6 Equity Volatility Carry Exposures

Koijen, Moskowitz, Pedersen, and Vrugt (2013) examine carry across global equities, fixed income, foreign exchange, commodities, treasuries, credit, equity index call options and put options. Table 26 holds the summary statistics of carry on the nine assets along with the correlation matrix including the long-short equity volatility carry portfolio from Table 20 from 1996 through September, 2012.[18] While the long/short equity volatility carry portfolio posts a much higher Sharpe Ratio (7.12), the after transactions costs long carry portfolio's Sharpe Ratio, 1.39, is within the range seen here: from 0.19 for global equities to 1.52 for equity index option puts. The equity volatility correlations range from 0.025 with one version of the global bond carry to -0.175 for the credit portfolio.[19] The correlations for the equity volatility portfolio with the index call and put options are both negative (-0.171 and -0.133).

By volatility-weighting the nine different strategies, a diversified carry portfolio produces a Sharpe Ratio of 1.18, higher than that of the traditional foreign exchange portfolio, 0.66.[20] The diversified carry portfolio, however, remains exposed to liquidity and volatility.[21] Table 27 examines the exposure of the volatility carry portfolio to excess market returns, the small minus big (SMB) and high minus low (HML) returns of Fama and French (1992); momentum portfolio returns of Carhart (1997); traded liquidity portfolio (Liq) returns of Pástor and Stambaugh (2003); Coval and Shumway (2001) zero beta straddle (zbr) returns; and the diversified carry portfolio of Koijen, Moskowitz, Pedersen, and Vrugt (2013). The zbr and Liq portfolios proxy for market volatility and liquidity, respectively. The volatility carry portfolio loadings on all factors are insignificant with the exception of the HML portfolio at the 10% level and the excess market returns at the 0.1%

[18]The data used here is obtained from the website of Lasse H. Pedersen.

[19]Koijen, Moskowitz, Pedersen, and Vrugt (2013) decomposes bond carry into the bond's yield spread to the risk free rate (slope), and the price roll down the yield curve (level).

[20]Koijen, Moskowitz, Pedersen, and Vrugt (2013) follow the volatility-weighting procedures of Asness, Moskowitz, and Pedersen (2013) by normalizing each strategy to a 10% annual volatility.

[21]Koijen, Moskowitz, Pedersen, and Vrugt (2013).

level; both coefficients, however, are negative. Constants for the four regressions are significantly positive, at roughly 50%. Since it is shown that transactions costs have a significant impact on returns, the loadings of the after transactions cost long volatility carry portfolio on the above factors is examined in Table 28. The portfolio similarly loads significantly negatively on the market, and while it loads negatively on the aggregate volatility factor, zbr, the magnitude, -0.10, is economically insignificant. The constants for the four regressions are positive and significant, ranging from 10.5% to 12.0%. Figures 9 and 10 graphically illustrate the differences in returns by displaying the equity graphs of investments in the equity volatility carry portfolios and the diversified carry portfolio. Unlike a diversified carry portfolio, the returns to equity volatility carry are not exposed to market, liquidity, or volatility factors.

2.7 Conclusion

The carry trade has been shown to exist across asset classes. In index options and volatility, the trade has been shown to produce significant positive returns, as forward volatility poorly predicts future spot volatility. As the index and equity volatility term structure dynamics differ, I examine whether the carry trade exists in the equity volatility market by first synthesizing forward variance swaps. I find that forward variance poorly predicts future spot variance, and a carry trade effected on these hypothetical swaps would prove profitable. I then turn to an investable version of the carry trade by employing calendar spreads. The returns to carry here are arbitrage-like; after incorporating transactions costs, I find that the long volatility carry trade produces significantly positive returns which are negatively exposed to both market and volatility risks. After further examination, I find that size, liquidity and trade tenor impact returns, although none completely explain the performance. The findings are supportive of the Campasano and Linn (2017) volatility framework and demand based options pricing model of Garleanu, Pedersen, and Poteshman (2009).

CHAPTER 3

BEATING THE S&P 500 INDEX

3.1 Introduction

The covered call is perhaps the most basic options strategy: a call option is sold against a long position in an asset. The premium collected on the option softens any losses should the asset price decline; in exchange, the asset may be called away if the price of the asset exceeds the strike price at expiration. The strategy can be performed using any asset in a cash account, as long as options can be written on it. Asset managers often engage in this strategy against core equity and/or equity index positions; a suite of covered call indexes are published by the Chicago Board Options Exchange (CBOE). When executed on a broad-based index, the strategy typically outperforms the underlying on a risk-adjusted basis. Kapadia and Szado (2007) and Israelov and Nielsen (2014), among others, show that this outperformance is borne from the risk premium inherent in the short call.[1] While systematically writing options against a long index position has been shown to outperform the underlying, the allocation to the two risk premia, market and volatility, is fixed: the portfolio invests fully in the index and call options are written against the position. In this study I allow the allocations to volatility and the market to vary over time. Instead of expressing the volatility exposure through short options, I pair an index position with VIX futures due to its independence to path and time. This two asset portfolio created outperforms that of the index on both a risk adjusted and absolute basis. When accounting for the

[1] See also Hill, Balasubramanian, Gregory, and Tierens (2006).

expected returns to volatility conditional on term structure slope, a naive portfolio produces a Sharpe Ratio 25% higher than that of the index, and bests covered call strategies. A portfolio optimized *ex ante* triples index performance with similar return volatility and more than doubles the risk-adjusted performance of covered call strategies.

The Chicago Board Options Exchange introduced its Buy Write Monthly Index (BXM) in 2002. The Index consists of two components: a long position in the S&P 500 Index and a short at the money (ATM) one month call written on the Index. The strategy is implemented systematically: a one month, ATM call is written on the index and the call is cash settled at expiration, at which time another one month ATM call is sold. In examining the historical performance of the BXM from June, 1988 through 2001, Whaley (2002) finds that the strategy posts an average monthly return of 1.106% vs. the S&P 500 Index's 1.187%, with volatility roughly two-thirds that of the S&P 500. In addition to a higher Sharpe Ratio, the strategy also posts a positive Jensen's alpha (0.23%). In concluding, Whaley posits that, in an efficient market, the risk adjusted returns of the two should not differ, and perhaps demand pressure on S&P 500 Index options produces the outperformance.

Kapadia and Szado (2007) study the returns of the covered call strategy executed on the Russell 2000 Index from 1996-2006. Similar to Whaley, the covered call strategy on the Russell 2000 Index outperforms the index on a risk-adjusted basis. While the absolute returns approximately match that of the index itself, the standard deviation is lower by roughly one-third. In dissecting their sample period, they also find that the strategy outperforms the index from 2003 to 2006, a relatively unfavorable period for the strategy due to the combination of persistently high index returns and low volatility. By decomposing the returns to the short call position, it is shown that the implied volatility of the call option sold is higher on average than the volatility realized over the life of the option, and if the implied volatility of the call option equaled the volatility subsequently realized by the index, the short calls would have generated a significant loss. This echoes earlier studies by Bakshi and Kapadia (2003a), Coval and Shumway (2001), and Carr and Wu (2009) which show that a volatility risk premium exists: selling index options produce significant returns.

Since a covered call strategy typically is implemented passively by selling call options systematically and then exiting the position at the option's expiration, the path of the underlying can influence the degree to which the strategy outperforms the index. During a prolonged rally, the returns will look relatively poor as the call sales act to cap the gains on the underlying index, and as the market falls, the protection is limited to the premium collected. Israelov and Nielsen (2014) further decompose the strategy to isolate the risk premium and the impact of the path of the underlying. At inception, an ATM covered call position can be viewed as two separate positions: A long position in the underlying equal to one half of the index position, and a short volatility exposure where the other half of the index position acts to delta hedge the short call. The hedge needed is not static, however, as the call delta changes with the index level. The returns of the covered call, then, can be parsed into three exposures:

- Passive Equity, equal to the Equity $*$ (1- Initial Call Delta);
- Short Volatility, equal to - (Call - Current Delta $*$ Equity); and
- Dynamic Equity, equal to Equity $*$ (Initial Call Delta - Current Call Delta).

To illustrate with an example, assume the price of the index is 100, as is the strike of the call sold. The call delta is 0.50, and the price of the option is \$4.00. \$1,000,000 of the index is purchased, and so \$40,000 in premium is collected. The exposures are:

- Passive Equity: $(1 - 0.50) * \$1,000,000 = \$500,000$ Equity
- Short Volatility: $-(Call - 0.50 * \$1,000,000) = -Call + \$500,000$ Equity
- Dynamic Equity: $(0.50 - 0.50) * \$1,000,000 = \$0$.

If the index rises to 102, and the call delta increases to 0.70, then the three exposures become:

- Passive Equity: $(1 - 0.50) * \$1,020,000 = \$510,000$ Equity
- Short Volatility: $-(Call - 0.70 * \$1,020,000) = -Call + \$714,000$ Equity
- Dynamic Equity: $(0.50 - 0.70) * \$1,020,000 = -\$204,000$.

The first two components provide exposure to the equity and volatility risk premia. The passive equity component increases by 2% as the index rallies 2%. The short volatility position necessitates a larger index position in order to hedge the option, as the delta has increased from 0.50 to 0.70. Since a larger index position is needed to hedge the short option, the dynamic equity factor falls. Assuming a positive market risk premium, the expected return of the dynamic equity factor is at best zero. Israelov and Nielsen (2015) show that actively managing the covered call to mute this exposure improves the risk-adjusted returns. The resulting portfolio produces superior risk-adjusted returns to both the traditional covered call strategy and the index, and eliminates the return asymmetry in up and down markets present in the traditional covered call strategy. The absolute returns, however, lag the index, the position requires active management, and unlike the traditional covered call strategy, the rehedging of the option requires a margin account.

Israelov and Nielsen (2015) neutralize the dynamic equity component of the traditional covered call to produce a structure capturing market and volatility risk premia. As documented by Bakshi and Kapadia (2003a), among others, the volatility risk premia is larger and distinct from the market premia, and as Kapadia and Szado (2007) illustrates, it drives the outperformance of the covered call strategy. Here I show that substituting a short VIX futures exposure for short options produce a portfolio with similar risks and returns of the hedged covered call strategy. As understanding of the volatility risk premia has evolved, studies have shown that the term structure slope is a powerful predictor of returns to volatility assets: Simon and Campasano (2014) show that, for VIX futures, the volatility expectations hypothesis fails to hold, and the VIX futures basis holds predictive power over VIX futures returns. Johnson (2016) shows that term structure slope predicts excess returns for S&P 500 Index variance swaps and delta hedged option positions in addition to VIX futures. The fact that the expectations hypothesis fails presents a puzzle, as an inverted term structure cheapens the cost of volatility as market risk is increasing. Cheng (2016) shows this is not a function of mismeasurement, and finds that demand for VIX futures drops during these episodes of increasing risk.

While the covered call strategy holds fixed the allocation to both market and volatility premia, I incorporate the findings of the term structure studies, allowing the allocations between market and volatility to vary over time. Using VIX futures instead of S&P 500 Index options to express the volatility view enable investors to gain volatility exposure more easily given the independence to the path of the underlying for VIX futures. Following the procedure in Simon and Campasano (2014) and Cheng (2016), I first condition the volatility investment on the sign of the slope of the VIX term structure using the weightings of a covered call; the resulting portfolio bests the hedged covered call strategy. I then optimize *ex ante* using a long-term historical measure of market returns, and the VIX futures basis, the forward-looking measure of the difference between the VIX futures and the VIX Index. The portfolio holding VIX futures, the S&P 500 Index, and cash triples the returns of the index and more than doubles the risk-adjusted returns of covered call strategies.

In the next section, I review the characteristics of covered call strategies; in Section 3.3 I discuss VIX futures and volatility risk premia. Section 3.4 describes the time varying allocation optimization process and results. Section 3.5 concludes this chapter.

3.2 Covered Calls

Table 29 provides summary statistics for the S&P 500 Index, the covered call strategy executed on the S&P 500 Index, and the hedged covered call strategy following the Israelov and Nielsen (2015) process from 1996 through 2015. Monthly statistics are calculated over the standard option expirations. On each expiration day, the lowest strike call option out of the money is sold and the option expiring is cash settled. Over the life of the option, the hedged covered call strategy adjusts the index position daily such that the entire position's delta remains at 0.50.

The monthly returns for both covered call strategies are approximately 10 basis points lower than the index returns, but the covered call monthly standard deviation is 30% lower (0.0339 vs. 0.0493), and the standard deviation for the hedged covered call is 42% lower (0.0284). As a result, the Sharpe Ratios of the covered call, 0.47, and hedged covered call, 0.57, are higher than that of the index, 0.39. Due to the asymmetry of the covered call, the strategy is more negatively skewed, and its downside beta, 0.87, is higher than both its beta, 0.60, and upside beta, 0.39. The hedged strategy addresses this asymmetry. The three measures of beta are approximately equal (0.56, 0.55, and 0.58 for its beta, upside beta, and downside beta, respectively) and its skewness is less negative (-1.32 vs. -1.99). Finally, the extreme variation of the hedged covered call is less than that of the covered call and the index. The lowest returns for the three strategies, occurring during the October, 2008 expiration, are 21.38%, 18.82%, and 13.80% for the index, covered call, and hedged covered call strategies, respectively; the highest returns occur two months later (17.73%, 14.55%, and 10.05%).

Table 30 decomposes the returns of both versions of the covered call strategies into two components. Panel A parses the returns of the covered call into the index and short call option. Panel B splits the returns into an index position equal to 50% of the entire position, and the short call, delta hedged daily with a target delta of 0.50 to maintain the index exposure at inception. It is unsurprising that the returns to the short ATM call are negative, losing ten basis points on average. The resulting portfolio, however, posts higher risk-adjusted returns. Kapadia and Szado (2007) showed that the implied volatility at which the call is sold was consistently higher than the volatility subsequently realized by the index, producing the higher risk-adjusted returns. This is seen more directly in Panel B of Table 30. Here the hedged covered call position is separated into the delta hedged call and the index. The delta hedged call produces a high Sharpe Ratio, 1.55, with virtually no beta, and the strategy produces higher risk-adjusted returns and lower downside risk over the covered call and the index.

3.3 VIX Products

Variance swaps allow sellers to gain short volatility exposure independent of the path of the underlying where the payoff is determined by the difference between the variance implied by option prices and that realized by the index. However, these products are only available over-the-counter.[2] VIX futures provide exposure to future levels of the VIX Index. The Index itself is a measure of 30 day volatility, and is derived using the prices of options, as follows:

$$\sigma^2 = \frac{2}{T}\sum_i \frac{\Delta Ki}{K^2} e^{RT} Q(K_i) - \frac{1}{T}[\frac{F}{K_0} - 1]^2$$

where:

- $\sigma = \frac{VIX}{100}$,
- T=time to expiration,
- F = forward index level,
- K_0 is the first strike below the forward index level,

[2]The Chicago Board Options Exchange lists a product similar to a variance swap but it is not actively traded.

- K_i is the strike price of an OTM option (calls where the strike price is greater than the forward price, puts where the strike price is less than the forward price),
- ΔK_i is the interval between strike prices,
- R is the interest rate, and
- $Q(Ki)$ is the midpoint between the bid and the ask of the option price.

While it is theoretically possible to construct a position in the VIX Index, the daily rebalancing costs would prove prohibitive. VIX futures, however, allow investors to express a view on index volatility. The resulting exposure is not identical to that of delta hedged options, as the underlying volatility does not enter directly into the returns to VIX futures, but the correlation of VIX futures and delta hedged call returns is fairly high at 0.69. Table 31 contains the returns of the delta hedged call and a constant maturity one month VIX future over 2007 through 2015. The sample period is shortened here as prior to 2007 VIX futures were thinly traded and not listed monthly. The constant maturity one month VIX futures position is calculated by rolling daily, in equal amounts, a position from the front month contract to the second month contract in order to maintain the one month maturity, following the methodology which determines the S&P 500 VIX Short-Term Futures Index.[3] The daily returns are then calculated according to the position held each day. A constant maturity VIX future is used in order to maintain a constant exposure, as the beta of the VIX future with respect to the VIX index increases as it approaches expiration: Figure 11 plots the beta of the front month VIX futures with respect to the VIX Index according to the days until expiry. As the front month VIX future approaches expiry, its beta with respect to the VIX index increases driving higher its volatility.

[3]See http://us.spindices.com/indices/strategy/sp-500-vix-short-term-index-mcap for a detailed description of the index. Exchange traded products such as VXX and VIXY offer exposure to the VIX short-term futures index.

Since each portfolio is fully invested in the short volatility instrument, the returns and volatility are higher than the returns attributed to the short volatility in Table 30. The delta hedged call option returns are calculated following the methodology in Frazzini and Pedersen (2012). At trade inception, I start with $1 worth of calls, $V_0 = 1$. Each day, the value of the portfolio is computed iteratively as follows:

$$V_t = V_{t-1} + x(F_t - F_{t-1}) - x\Delta_{t-1} r_t^S S_{t-1} + r_t^f (V_{t-1} - xF_{t-1} + x\Delta_{t-1} S_{t-1}) \quad (3.1)$$

where $x = 1/F_0$, the number of options contracts; F is the option price; r^s is the daily stock return; r^f is the daily risk free rate; and Δ is the option's delta. The second term above represents the dollar return from the change in option price, the profit or loss from the delta hedge is computed in the third term. The final term calculates the financing cost of the position. The return to the position, R_T, is

$$R_T = V_T - V_0 = V_T - 1 \quad (3.2)$$

The constant maturity VIX future produces a lower Sharpe Ratio, 0.51, than the short delta hedged call, 0.68. Examination of the betas listed reveal that the upside beta of the delta hedged ATM call, 1.05, is much lower than the beta, 2.43, and downside beta, 2.58. The difference in betas for the VIX future is greater, with the downside beta, 3.83, and beta, 2.38, standing higher than the upside beta, 0.29. Another notable difference is the returns of the delta hedged call in Table 30 and 31. Over the entire sample from 1996 through 2015, the returns to delta hedged calls decrease from the first half to the second; the fact that the financial crisis lies in the second half of the sample does not account solely for this difference.

While the returns from short VIX futures fall short of delta hedged option returns, the constant maturity VIX futures are used in the study for their path and time independency and ease in varying exposures. Studies have shown that a significant predictor of volatility returns is term structure slope. Simon and Campasano (2014) first document that VIX futures levels are poor predictors of the VIX Index, and the basis, the difference between the VIX futures and the Index, predicts VIX futures returns: selling VIX futures when the term structure is upward sloping and buying VIX futures when the term structure is downward sloping produce significant returns. Given this, in Table 32, I examine the short volatility exposures conditional on the sign of the VIX futures term structure slope, where:

$$Slope = \frac{ConstantOneMonthVIXFuture}{VIXIndex} - 1 \tag{3.3}$$

Each day, the slope is examined. If positive, the position is held; if negative, the position is closed.[4] Over the entire sample, the slope is positive 76.6% of the time. The returns for the delta hedged call drop when conditioning on term structure slope, but in keeping with the covered call strategy, the option originally sold at the beginning of each expiration period is the option traded over the life of that expiration cycle. Term structure inversion typically occurs after a market decline, and so exiting the short call position results in closing a low delta call with little optionality remaining. As VIX futures are path independent, conditioning on the sign of the term structure slope boosts absolute returns of the constant maturity VIX futures from 2.93% to 4.28%, with the Sharpe Ratio increasing from 0.51 to 1.16. The minimum return rises from -96.74% to -33.21%, as the term structure slope is negative for much of the latter part of 2008 during the financial crisis.

[4]Simon and Campasano (2014) and Cheng (2016) show that the costs to owning volatility may turn positive when the term structure slope inverts. Given that a covered call is essentially a long market, short volatility portfolio, the volatility positions held here are either short or flat.

3.4 Time-Varying Allocations

A covered call and the hedged covered call allocate between market and volatility premia. The covered call invests fully in the market and overwrites the position with an ATM call; the hedged covered call can be viewed as investing 50% of assets in the market and holding a short delta hedged ATM call with a notional value equal to the entire portfolio. Options investors typically express the size of volatility positions in terms of the vega, the sensitivity of the option price with respect to a one percentage point change in the option's implied volatility. While vega is positively related to the implied volatility of the option, the vega of the one month ATM option will remain roughly consistent. Table 33 examines the market/VIX futures portfolio where 50% of assets are invested in the market and the VIX futures component is set such that the sensitivity of the position with respect to volatility equals the vega of the short option. Included for comparison purposes are the S&P 500 Index, the covered call, and hedged covered call strategy. While both versions of the covered call are fully invested, and the hedged covered call will use leverage to delta hedge the option, the portfolio holding VIX futures allocates 2.47% on average to VIX futures, with a maximum allocation of 7.22%; greater than 40% of the position remains in cash. Panel A holds the unconditional returns of the strategies. While the covered call strategy has been shown to outperform the index on a risk-adjusted basis, during this sample period the covered call actually underperforms the index, posting a 0.39 Sharpe Ratio as compared to 0.42 for the index. The average returns across the three strategies are roughly consistent, ranging between 41 and 47 basis points monthly. The portfolio holding VIX futures underperforms the hedged covered call strategy, posting a Sharpe Ratio of 0.45 vs. 0.50, while having an exposure to the underlying index similar to that of the hedged covered call. Panel B holds the returns conditioned on the sign of the VIX futures slope. Each day, the VIX futures slope is calculated. If the slope is negative, the position is exited; if the slope is positive, the position remains on or is entered if no position exists.[5] Here, the VIX portfolio outperforms, posting a 0.54 Sharpe Ratio with similar skewness to the index and hedged covered call and a minimum return of 10.69% compared to 21.37% and 11.04% for the index and hedged covered call respectively. Conditioning on term structure slope sign produces a portfolio with a Sharpe Ratio 10% higher than the hedged covered call and 28% higher than the S&P 500 Index.

Since the portfolio holding VIX futures is not fully invested, as the relatively modest allocation to VIX futures averages 2.47%, Table 34 increases the fixed allocation to VIX futures. As with Table 33, Panel A includes unconditional returns and Panel B holds the returns conditional on term structure slope sign. Three allocations, 2, 5, and 10% are included, with a 2% allocation matching roughly the portfolio from Table 33. In Panel A, the monthly returns and Sharpe Ratios increase as the VIX futures exposure increases. Betas become more asymmetrical as well; at a 10% allocation the downside beta, 0.88, is greater than the beta 0.74, and upside beta, 0.53. These patterns persist in Table B, except for the beta asymmetry; conditioning on term structure slope sign mutes the differential between up and down beta. The portfolio allocating 10% has a 0.75 Sharpe Ratio, posting returns 13% higher with volatility 38% lower than the index. The results here in Table 34 illustrate that the composition of a covered call is suboptimal when viewed from the standpoint of a portfolio allocating to market and volatility premia.

Until now the study has conditioned on the sign of the term structure slope; when the futures slope is negative, the allocation to volatility is closed. Cheng (2016) showed that the magnitude of the *ex ante* premium, however, predicts returns with a coefficient close to one. In order to incorporate the magnitude of the VIX basis, I create an optimal portfolio using the VIX basis as the expected return of the VIX futures position. A ten year historical average return of the S&P 500 Index is used as the expected return of the index to obtain a measure of

[5]For the hedged covered calls, the option sold at the beginning of the expiration cycle is the option resold if the position was exited previously.

market risk premia.[6] The daily returns of the past one month are used to calculate expected return variance. Each day, the S&P 500 Index and short VIX futures weightings are determined by maximizing the Sharpe Ratio.[7] Specifically,

$$\max_{w_{VIX},w_{MKT}} \frac{w_{VIX} * E(R_{VIX}) + w_{MKT} * E(R_{MKT}) - R_{rf}}{\sqrt{w_{VIX}^2 * \sigma_{VIX}^2 + w_{MKT}^2 * \sigma_{MKT}^2 + 2 * w_{VIX} * w_{MKT} * \sigma_{VIX,MKT}^2}} \tag{3.4}$$

subject to:

$$0 \leq w_{VIX} \leq 1,$$
$$0 \leq w_{MKT} \leq 1,$$
$$w_{VIX} + w_{MKT} = 1$$

where:

- w_{VIX} is the allocation to the constant maturity VIX futures;
- w_{MKT} is the allocation to the S&P 500 Index;
- $E(R_{MKT})$ is the expected return of the S&P 500 Index using a long-term average;
- $E(R_{VIX})$ is the expected return of the VIX futures position using VIX futures basis;
- R_{rf} is the risk-free rate;
- σ_{MKT}^2 is the expected variance of index returns using the prior month's daily returns;
- σ_{VIX}^2 is the expected variance of VIX futures returns using the prior month's daily returns; and

[6]Unreported examinations using shorter time periods produce substantially similar results.

[7]Calculating the portfolio weightings and then adjusting the portfolio the following day produce substantially similar results.

- $\sigma^2_{VIX,MKT}$ is the expected covariance of the VIX futures and S&P 500 Index using the prior month's daily returns.

The Optimized Portfolio in Table 35 is produced by maximizing Equation 3.4. Figure 12 displays a histogram of the allocation to VIX futures. The portfolio returns 5% monthly, with a 1.23 Sharpe Ratio, but as it invests entirely in a short VIX futures position over 60% of the time, the return volatility, 14%, is more than double that of the index and more than four times larger than that of the hedged covered call. Due to this relatively high volatility, I also include the Volatility Targeted Optimized Portfolio, which is designed to produce a return volatility similar to that of the S&P 500 Index. Each day, the positions are scaled so that the expected portfolio volatility equals the expected volatility of the market. As the Optimized Portfolio holds the portfolio with the highest expected Sharpe Ratio, the Volatility Targeted Optimized Portfolio is the portfolio on the Security Market Line which allocates to the Optimized Portfolio and cash in an effort to target the return volatility of the S&P 500 Index. The Volatility Targeted Optimized Portfolio returns 2.02% on average each month, triple that of the index, with a monthly return volatility of 5.95%, slightly higher than the S&P 500 Index volatility (5.56%). In contrast to portfolios examined earlier, the upside beta, 1.06, is higher than the beta, 0.95, and downside beta, 0.89, while the skewness, -1.15, is close to that of the Index, -1.07. Figure 13 holds the allocations to VIX Futures, the S&P 500 Index, and cash for the Volatility Targeted Optimized Portfolio. The portfolio invests on average less than half of assets, with the average cash holding equal to 51.8%; an average index weight of 33.1% and average VIX futures weight of 23.4%. The allocation to the market over time resembles a barbell, with no position held roughly 60% of the time and a fully invested index portfolio about 30% of the sample. An investment in VIX futures greater than 50% occurs 7% of the time, during the market rebound in 2009, when the VIX was elevated and the VIX futures term structure slope was positive.

Figure 14 plots the equity curves of the index, the covered call, the hedged covered call, and the Volatility Targeted Optimized Portfolio. The curves show the Optimized Portfolio posts fairly consistent returns following the crisis, with downturns in 2010, 2011 and 2014, consistent with the S&P 500 Index. The outperformance is not driven by a segment of the sample. Allowing the allocations to vary over time by conditioning on the VIX futures slope produces a portfolio superior to the covered call and hedged covered call of Israelov and Nielsen (2015).

3.5 Conclusion

Overwriting an index position with options is a strategy commonly executed and creates a portfolio with exposures to market and volatility risk premia and an equity timing component; removing the equity timing component has been shown to improve portfolio performance. The allocations to volatility and market premia, however, remain fixed. While it remains a puzzle that the cost of owning volatility decreases during periods of increasing risk, prior studies have demonstrated that term structure slope is predictive of returns. By using the VIX basis as an *ex ante* measure of expected return, I allow for time-varying allocations. I show that a three asset portfolio holding a VIX futures position, index, and cash with volatility roughly equal to that of the S&P 500 Index triples the returns of the index and more than doubles the risk-adjusted returns of both versions of the covered call.

Table 1: Volatility Risk Premia for Portfolios

This table reports the average volatility risk premiums of the straddles contained in each portfolio, as defined by $\frac{IV}{RV} - 1$, where for each ATM straddle in each portfolio, IV is the implied volatility of the ATM straddle, RV is the annualized volatility realized by the underlying over the period equal to the straddles' maturity. (For example, the three month portfolios use three month annualized realized volatility.) Portfolio 1 holds straddles which have the most upward sloping term structure, as defined by $\frac{1mIV}{6mIV} - 1$; Portfolio 10 holds straddles which have the most inverted term structure. The period examined spans from January, 1996, to July, 2015, and includes 924,952 straddles across all maturities and 7,076 equities.

	Decile 1	2	3	4	5	6	7	8	9	Decile 10
1m	0.0690	0.0775	0.0909	0.1037	0.1119	0.1231	0.1348	0.1566	0.1907	0.3246
2m	0.0626	0.0460	0.0417	0.0441	0.0423	0.0451	0.0438	0.0538	0.0750	0.1442
3m	0.0617	0.0414	0.0397	0.0381	0.0350	0.0356	0.0330	0.0298	0.0391	0.0768
4m	0.0490	0.0273	0.0244	0.0209	0.0197	0.0175	0.0188	0.0216	0.0295	0.0579
5m	0.0359	0.0169	0.0130	0.0117	0.0064	0.0059	0.0054	0.0066	0.0092	0.0239
6m	0.0286	0.0072	0.0049	(0.0018)	(0.0029)	(0.0048)	(0.0075)	(0.0116)	(0.0108)	(0.0330)

Table 2: Summary Statistics of Implied Volatility by Decile and Maturity

This table reports the means, standard deviations, and skewness of the implied volatilities of portfolios of at the money (ATM) equity option straddles. Each month, the day following the standard options expiration, ten portfolios of options with maturities from one to six months are formed based on the volatility term structure. Portfolio 1 (10) holds straddles which have the most upward (downward) sloping term structure, as defined by $\frac{1mIV}{6mIV} - 1$. The period examined spans from January, 1996, to July, 2015, and includes 924,952 straddles across all maturities and 7,076 equities.

Panel A: Means of Implied Volatility by Decile and Maturity

	Decile 1	2	3	4	5	6	7	8	9	Decile 10	All deciles
1m	0.3594	0.3821	0.4010	0.4184	0.4335	0.4460	0.4600	0.4826	0.5076	0.5708	0.4461
2m	0.3869	0.3964	0.4085	0.4200	0.4319	0.4402	0.4516	0.4649	0.4807	0.5178	0.4399
3m	0.3972	0.3990	0.4062	0.4162	0.4258	0.4311	0.4409	0.4517	0.4629	0.4897	0.4321
4m	0.3923	0.3950	0.4082	0.4169	0.4238	0.4310	0.4390	0.4450	0.4593	0.4777	0.4288
5m	0.3923	0.3931	0.4014	0.4135	0.4219	0.4266	0.4324	0.4433	0.4475	0.4595	0.4231
6m	0.4007	0.3982	0.4036	0.4109	0.4171	0.4220	0.4266	0.4335	0.4385	0.4496	0.4201
All	0.3882	0.3940	0.4048	0.4160	0.4257	0.4328	0.4417	0.4535	0.4661	0.4942	0.4317

Panel B: Standard Deviations of Implied Volatility by Decile and Maturity

	Decile 1	2	3	4	5	6	7	8	9	Decile 10	All deciles
1m	0.1091	0.1186	0.1230	0.1253	0.1281	0.1284	0.1286	0.1333	0.1416	0.1545	0.1424
2m	0.1036	0.1099	0.1129	0.1139	0.1160	0.1171	0.1167	0.1195	0.1274	0.1359	0.1235
3m	0.1022	0.1114	0.1110	0.1127	0.1141	0.1138	0.1157	0.1151	0.1206	0.1284	0.1179
4m	0.1002	0.1022	0.1061	0.1105	0.1109	0.1105	0.1079	0.1109	0.1196	0.1292	0.1139
5m	0.1002	0.1042	0.1027	0.1067	0.1028	0.1051	0.1042	0.1044	0.1122	0.1116	0.1075
6m	0.0973	0.1050	0.1045	0.1048	0.1055	0.1050	0.1048	0.1010	0.1055	0.1102	0.1055
All	0.1029	0.1087	0.1101	0.1124	0.1131	0.1137	0.1137	0.1155	0.1236	0.1352	0.1194

Table 2 cont.: Summary Statistics of Implied Volatility by Decile and Maturity

Panel C: Skewness of Implied Volatility by Decile and Maturity

	Decile 1	2	3	4	5	6	7	8	9	Decile 10	All deciles
1m	0.8435	0.8204	0.8214	0.8510	0.8582	0.9017	0.9802	1.1051	1.2608	1.5439	1.0302
2m	0.8129	0.8121	0.8285	0.8543	0.8817	0.9427	0.9745	1.1031	1.2514	1.5400	1.0406
3m	0.8166	0.7921	0.8392	0.8964	0.9014	0.8957	1.0443	1.1149	1.1592	1.4084	1.0068
4m	0.8306	0.8861	0.7800	0.8357	0.8947	0.9106	0.9489	1.0749	1.1997	1.5725	1.0551
5m	0.7615	0.8506	0.8318	0.8787	0.8201	0.8684	0.8357	0.9595	1.2468	1.3486	0.9271
6m	0.8599	0.8082	0.8619	0.8871	0.9352	0.9166	0.9466	1.0290	1.1115	1.3728	0.9574
All	0.7676	0.8105	0.8243	0.8716	0.8994	0.9318	0.9949	1.1303	1.2695	1.5230	1.0654

Table 3: Movements of One Month Implied Volatility vs. Six Month Implied Volatility

Each month, the portfolios are formed based on the implied volatility term structure. Portfolio 1 holds straddles which have the most upward sloping term structure, as defined by $\frac{1mIV}{6mIV} - 1$; Portfolio 10 holds straddles which have the most inverted term structure. The changes in one and six month implied volatility for each firm in each portfolio are calculated, and then averaged for each month for each decile. Reported below are the results of regressing the change in one month volatility on the change in six month volatility for each decile and for the entire sample. The period examined spans from January, 1996, to July, 2015, and includes 924,952 straddles across all maturities and 7,076 equities.

	Decile 1	2	3	4	5	6	7	8	9	Decile 10	All
b_{6mIV}	1.301***	1.356***	1.454***	1.488***	1.548***	1.522***	1.635***	1.604***	1.637***	1.734***	1.585***
	(0.0677)	(0.0702)	(0.0778)	(0.0779)	(0.0825)	(0.0873)	(0.0928)	(0.0947)	(0.103)	(0.120)	(0.0261)
$cons$	-0.118***	-0.0647***	-0.0391***	-0.0218***	-0.00620	0.0111*	0.0285***	0.0517***	0.0940***	0.203***	0.014***
	(0.0041)	(0.0044)	(0.0048)	(0.0049)	(0.0052)	(0.0056)	(0.0060)	(0.0066)	(0.0075)	(0.0094)	(0.0016)
R-squared	0.615	0.617	0.601	0.611	0.603	0.567	0.572	0.553	0.519	0.473	0.611

Table 4: Explanatory Power of Realized Volatility on Implied Volatility

Each month, for each portfolio, the ATM implied volatility of each firm is regressed on the firm's one month and one year annualized realized volatility calculated using daily closes of the underlying. The coefficients and standard errors reported are the time series averages of the cross-sectional regressions. Each month, the portfolios are formed based on the implied volatility term structure. Portfolio 1 holds straddles which have the most upward sloping term structure, as defined by $\frac{1mIV}{6mIV} - 1$; Portfolio 10 holds straddles which have the most inverted term structure. The period examined spans from January, 1996, to July, 2015, and includes 924,952 straddles across all maturities and 7,076 equities.

Panel A: One month implied volatility regressed on one month realized volatility

	Decile 1	2	3	4	5	6	7	8	9	Decile 10	All deciles
b_{RV}	0.5821***	0.5820***	0.5848***	0.5689***	0.5622***	0.5573***	0.5523***	0.5561***	0.5408***	0.5244***	0.5619***
	(0.0512)	(0.0492)	(0.0492)	(0.0482)	(0.0485)	(0.0489)	(0.0499)	(0.0499)	(0.0509)	(0.0674)	(0.0177)
$cons$	0.1564***	0.1660***	0.1768***	0.1900***	0.2005***	0.2104***	0.2244***	0.2365***	0.2599***	0.3275***	0.2114***
	(0.0202)	0.0201)	0.0206)	0.0210)	(0.0218)	(0.0223)	(0.0234)	(0.0240)	(0.0256)	(0.0350)	(0.0081)
R^2	0.5436	0.5681	0.5721	0.5688	0.5579	0.5533	0.5401	0.5477	0.5243	0.3940	0.4924

Panel B: One month implied volatility regressed on one year realized volatility

	Decile 1	2	3	4	5	6	7	8	9	Decile 10	All deciles
b_{RV}	0.6079***	0.6855***	0.6919***	0.7086***	0.7202***	0.7473***	0.7528***	0.7814***	0.8202***	0.8687***	0.7203***
	(0.0364)	(0.0322)	(0.0326)	(0.0334)	(0.0345)	(0.0358)	(0.0373)	(0.0390)	(0.0447)	(0.0779)	(0.0168)
$cons$	0.0961***	0.0873***	0.1006***	0.1042***	0.1092***	0.1088***	0.1185***	0.1235***	0.1272***	0.1726***	0.1199***
	(0.0174)	(0.0152)	(0.0156)	(0.0163)	(0.0170)	(0.0175)	(0.0185)	(0.0195)	(0.0223)	(0.0386)	(0.0081)
R^2	0.7055	0.7995	0.7979	0.7964	0.7931	0.7933	0.7802	0.7808	0.7574	0.5540	0.6280

Table 4 cont.: Explanatory Power of Realized Volatility on Implied Volatility

Panel C: Six month implied volatility regressed on one month realized volatility

	Decile 1	2	3	4	5	6	7	8	9	Decile 10	All deciles
b_{RV}	0.7037***	0.6305***	0.6108***	0.5773***	0.5563***	0.5377***	0.5189***	0.5074***	0.4707***	0.3955***	0.4930***
	(0.0670)	(0.0533)	(0.0515)	(0.0490)	(0.0481)	(0.0472)	(0.0469)	(0.0456)	(0.0444)	(0.0456)	(0.0155)
cons	0.1786***	0.1769***	0.1821***	0.1909***	0.1970***	0.2019***	0.2101***	0.2143***	0.2262***	0.2557***	0.2216***
	(0.0255)	(0.0214)	(0.0212)	(0.0210)	(0.0213)	(0.0213)	(0.0217)	(0.0216)	(0.0221)	(0.0239)	(0.0070)
R^2	0.5099	0.5675	0.5715	0.5686	0.5579	0.5532	0.5403	0.5480	0.5245	0.4294	0.4926

Panel D: Six month implied volatility regressed on one year realized volatility

	Decile 1	2	3	4	5	6	7	8	9	Decile 10	All deciles
b_{RV}	0.7368***	0.7387***	0.7204***	0.7165***	0.7096***	0.7173***	0.7040***	0.7088***	0.7109***	0.6600***	0.6706***
	(0.0476)	(0.0344)	(0.0338)	(0.0335)	(0.0339)	(0.0344)	(0.0349)	(0.0352)	(0.0385)	(0.0491)	(0.0126)
cons	0.1047***	0.0928***	0.1028***	0.1042***	0.1070***	0.1047***	0.1110***	0.1120***	0.1109***	0.1352***	0.1234***
	(0.0222)	(0.0160)	(0.0160)	(0.0163)	(0.0166)	(0.0167)	(0.0172)	(0.0176)	(0.0192)	(0.0246)	(0.0061)
R^2	0.6794	0.8006	0.7981	0.7969	0.7934	0.7939	0.7807	0.7817	0.7598	0.6253	0.7140

Table 5: Impact of Realized Volatility on Term Structure

Each month, for each portfolio, the slope of the implied volatility term structure of each firm is regressed on the firm's one month and one year annualized realized volatility calculated using daily closes of the underlying. The coefficients and standard errors reported are the time series averages of the cross-sectional regressions. Each month, the portfolios are formed based on the implied volatility term structure. Portfolio 1 holds straddles which have the most upward sloping term structure, as defined by $\frac{1mIV}{6mIV} - 1$; Portfolio 10 holds straddles which have the most inverted term structure. The period examined spans from January, 1996, to July, 2015, and includes 924,952 straddles across all maturities and 7,076 equities.

Panel A: Term structure regressed on one month realized volatility

	Decile 1	2	3	4	5	6	7	8	9	Decile 10
b_{RV}	0.412***	0.385***	0.352***	0.326***	0.299***	0.288***	0.266***	0.242***	0.221***	0.127***
	(0.0238)	(0.0245)	(0.0258)	(0.0267)	(0.0274)	(0.0280)	(0.0292)	(0.0286)	(0.0287)	(0.0310)
cons	-0.295***	-0.219***	-0.178***	-0.145***	-0.114***	-0.0858***	-0.0530***	-0.0118	0.0431***	0.237***
	(0.00920)	(0.00990)	(0.0108)	(0.0116)	(0.0122)	(0.0128)	(0.0137)	(0.0139)	(0.0146)	(0.0167)
R^2	0.575	0.527	0.458	0.403	0.352	0.322	0.272	0.245	0.212	0.071

Panel B: Term structure regressed on one year realized volatility

	Decile 1	2	3	4	5	6	7	8	9	Decile 10
b_{RV}	0.355***	0.301***	0.254***	0.208***	0.176***	0.158***	0.130***	0.114***	0.0860**	-0.0328
	(0.0323)	(0.0331)	(0.0332)	(0.0343)	(0.0346)	(0.0355)	(0.0368)	(0.0372)	(0.0381)	(0.0431)
cons	-0.301***	-0.204***	-0.152***	-0.107***	-0.0690***	-0.0360**	0.00375	0.0446**	0.107***	0.317***
	(0.0146)	(0.0150)	(0.0154)	(0.0162)	(0.0167)	(0.0172)	(0.0181)	(0.0185)	(0.0192)	(0.0221)
R^2	0.354	0.273	0.209	0.143	0.105	0.083	0.053	0.041	0.023	0.003

Table 6: Reaction of Implied Volatility to Short Term Implied Volatility

Each month, firms are sorted twice. First, at t_0, they are sorted into quintiles, based on the implied volatility term structure, as measured by $\frac{1mIV}{6mIV} - 1$. Second, at t_1, within each quintile, firms are sorted based on the percentage change in one month implied volatility, two weeks subsequent to sorting based on term structure. At both points of formation, we average the one and six month implied volatility in each portfolio. For each of the 25 portfolios, we regress the average t_1 two and six month implied volatility on the contemporaneous, t_1, and lagged, t_0 measure of one month implied volatility. The period examined spans from January, 1996, to July, 2015, and includes 924,952 straddles across all maturities and 7,076 equities.

Two Month Options

	Term Structure Quintile				
Change IV: Quintile 1	1	2	3	4	5
Contemporaneous 1m IV	1.037***	0.963***	0.957***	0.863***	0.835***
	(0.0631)	(0.0671)	(0.0231)	(0.0198)	(0.0166)
Lagged 1m IV	-0.0214	0.0281	0.0188	0.111***	0.141***
	(0.0534)	(0.0635)	(0.0225)	(0.0199)	(0.0184)
Constant	0.0248***	0.0230***	0.0210***	0.0200***	0.0164***
	(0.0063)	(0.0051)	(0.0019)	(0.0019)	(0.00262)
R-squared	0.949	0.962	0.994	0.995	0.992
Quintile 2					
Contemporaneous 1m IV	0.995***	0.976***	0.899***	0.856***	0.830***
	(0.0326)	(0.0212)	(0.0190)	(0.0172)	(0.0147)
Lagged 1m IV	-0.00684	-0.00724	0.0692***	0.110***	0.146***
	(0.0278)	(0.0198)	(0.0182)	(0.0171)	(0.0166)
Constant	0.0209***	0.0205***	0.0166***	0.0151***	0.00806***
	(0.0031)	(0.0018)	(0.0018)	(0.0019)	(0.0024)
R-squared	0.985	0.995	0.996	0.995	0.994
Quintile 3					
Contemporaneous 1m IV	0.999***	0.951***	0.882***	0.876***	0.832***
	(0.0229)	(0.0172)	(0.0174)	(0.0173)	(0.0192)
Lagged 1m IV	-0.0250	0.0215	0.0726***	0.0796***	0.140***
	(0.0200)	(0.0159)	(0.0166)	(0.0171)	(0.0215)
Constant	0.0235***	0.0147***	0.0180***	0.0150***	0.00408
	(0.00233)	(0.00174)	(0.00190)	(0.00223)	(0.00361)
R-squared	0.992	0.996	0.996	0.995	0.988
Quintile 4					
Contemporaneous 1m IV	0.980***	0.920***	0.899***	0.861***	0.724***
	(0.0182)	(0.0163)	(0.0168)	(0.0175)	(0.0270)
Lagged 1m IV	-0.00230	0.0411***	0.0592***	0.0903***	0.255***
	(0.0152)	(0.0149)	(0.0160)	(0.0176)	(0.0312)
Constant	0.0162***	0.0146***	0.0116***	0.0132***	0.00366
	(0.00200)	(0.00190)	(0.00217)	(0.00261)	(0.00607)
R-squared	0.995	0.996	0.995	0.993	0.972
Quintile 5					
Contemporaneous 1m IV	0.918***	0.897***	0.858***	0.848***	0.681***
	(0.0141)	(0.0177)	(0.0206)	(0.0250)	(0.0310)
Lagged 1m IV	0.0333***	0.0507***	0.0845***	0.0955***	0.296***
	(0.0121)	(0.0162)	(0.0197)	(0.0260)	(0.0361)
Constant	0.0167***	0.0115***	0.0101***	0.00818**	-0.00291
	(0.00209)	(0.00239)	(0.00299)	(0.00403)	(0.00843)
R-squared	0.996	0.995	0.992	0.987	0.961

Table 6 cont.: Six Month Options

Quintile: Change IV	Term Structure Quintile 1	2	3	4	5
Quintile 1					
Contemporaneous 1m IV	1.119***	0.813***	0.746***	0.645***	0.571***
	(0.130)	(0.0839)	(0.0392)	(0.0342)	(0.0239)
Lagged 1m IV	-0.0701	0.117	0.160***	0.261***	0.336***
	(0.110)	(0.0793)	(0.0382)	(0.0344)	(0.0265)
Constant	0.0421***	0.0580***	0.0570***	0.0528***	0.0504***
	(0.0131)	(0.0064)	(0.0032)	(0.0033)	(0.0037)
R-squared	0.822	0.935	0.982	0.981	0.979
Quintile 2					
Contemporaneous 1m IV	0.972***	0.848***	0.711***	0.679***	0.564***
	(0.0429)	(0.0350)	(0.0336)	(0.0298)	(0.0240)
Lagged 1m IV	-0.0241	0.0442	0.177***	0.201***	0.337***
	(0.0366)	(0.0328)	(0.0323)	(0.0296)	(0.0270)
Constant	0.0481***	0.0531***	0.0481***	0.0458***	0.0336***
	(0.0041)	(0.0031)	(0.0032)	(0.0033)	(0.0039)
R-squared	0.971	0.984	0.984	0.983	0.981
Quintile 3					
Contemporaneous 1m IV	0.866***	0.791***	0.698***	0.657***	0.530***
	(0.0362)	(0.0336)	(0.0337)	(0.0306)	(0.0269)
Lagged 1m IV	0.0293	0.0941***	0.166***	0.195***	0.348***
	(0.0316)	(0.0311)	(0.0321)	(0.0302)	(0.0301)
Constant	0.0572***	0.0465***	0.0486***	0.0487***	0.0352***
	(0.00368)	(0.00341)	(0.00369)	(0.00393)	(0.00505)
R-squared	0.978	0.983	0.981	0.979	0.970
Quintile 4					
Contemporaneous 1m IV	0.810***	0.741***	0.704***	0.632***	0.453***
	(0.0336)	(0.0324)	(0.0322)	(0.0300)	(0.0315)
Lagged 1m IV	0.0709**	0.118***	0.145***	0.203***	0.417***
	(0.0281)	(0.0296)	(0.0306)	(0.0303)	(0.0364)
Constant	0.0515***	0.0479***	0.0447***	0.0463***	0.0311***
	(0.00369)	(0.00377)	(0.00416)	(0.00448)	(0.00710)
R-squared	0.979	0.981	0.978	0.974	0.948
Quintile 5					
Contemporaneous 1m IV	0.701***	0.690***	0.654***	0.624***	0.359***
	(0.0264)	(0.0308)	(0.0354)	(0.0347)	(0.0363)
Lagged 1m IV	0.113***	0.128***	0.165***	0.184***	0.471***
	(0.0226)	(0.0282)	(0.0338)	(0.0361)	(0.0422)
Constant	0.0558***	0.0441***	0.0364***	0.0362***	0.0291***
	(0.00390)	(0.00417)	(0.00514)	(0.00561)	(0.00986)
R-squared	0.980	0.979	0.970	0.967	0.922

Table 7: Straddle Returns Sorted by Term Structure

This table reports the returns of portfolios of ATM straddles created by sorting on the implied volatility term structure. Portfolio 1 holds straddles which have the most upward sloping term structure, as defined by $\frac{1mIV}{6mIV} - 1$; Portfolio 10 holds straddles which have the most inverted term structure. The portfolios listed contain options of one to six months maturity, respectively, and the returns of a long/short portfolio which owns 6 month options and shorts 1 month options for each decile. The period examined spans from January, 1996, to July, 2015, and includes 924,952 straddles across all maturities and 7,076 equities.

One Month Options: Held for Two Weeks

Deciles	1	2	3	4	5	6	7	8	9	10	10-1
Returns	0.0315***	0.0182*	0.0086	0.0042	0.0032	0.0045	0.0030	0.0021	-0.0079	-0.0239***	-0.0554***
St. Error	(0.0079)	(0.0082)	(0.0077)	(0.0077)	(0.0075)	(0.0076)	(0.0077)	(0.0072)	(0.007)	(0.0061)	(0.0053)

One Month Options: Held Until Expiry

Deciles	1	2	3	4	5	6	7	8	9	10	10-1
Returns	0.0255	0.0040	-0.0141	-0.0336*	-0.0330*	-0.0336*	-0.0452***	-0.0530***	-0.0744***	-0.1185***	-0.1441***
St. Error	(0.0195)	(0.0192)	(0.0182)	(0.0182)	(0.0177)	(0.0175)	(0.017)	(0.0169)	(0.0154)	(0.0137)	(0.0118)
Sharpe Ratio	0.273	0.017	-0.190	-0.434	-0.437	-0.459	-0.608	-0.714	-1.117	-1.964	-2.723

Two Month Options

Deciles	1	2	3	4	5	6	7	8	9	10	10-1
Returns	0.0246**	0.0210**	0.0152	0.0131	0.0109	0.0156	0.0145	0.0150	0.0077	-0.0045	-0.0291***
St. Error	(0.0104)	(0.0104)	(0.0101)	(0.0099)	(0.0099)	(0.0099)	(0.0095)	(0.0095)	(0.0093)	(0.0082)	(0.0055)

Three Month Options

Deciles	1	2	3	4	5	6	7	8	9	10	10-1
Returns	0.0225***	0.0200**	0.0187**	0.0196**	0.0172**	0.0184**	0.0173**	0.0233***	0.0236***	0.0168**	-0.0057
St. Error	(0.008)	(0.0083)	(0.0076)	(0.0078)	(0.0079)	(0.0073)	(0.0076)	(0.0078)	(0.008)	(0.0071)	(0.0052)

Table 7, cont. Four Month Options

Deciles	1	2	3	4	5	6	7	8	9	10	10-1
Returns	0.0129**	0.0135*	0.0135**	0.0084	0.0131**	0.0199***	0.0195***	0.0198***	0.0160**	0.0188***	0.0058*
St. Error	(0.0065)	(0.007)	(0.0067)	(0.0065)	(0.0063)	(0.007)	(0.0064)	(0.0067)	(0.0063)	(0.0061)	(0.0038)

Five Month Options

Deciles	1	2	3	4	5	6	7	8	9	10	10-1
Returns	0.0065	0.0103*	0.0118**	0.0130**	0.0163***	0.0171***	0.0193***	0.0238***	0.0205***	0.0279***	0.0214***
St. Error	(0.0057)	(0.0057)	(0.0057)	(0.0057)	(0.006)	(0.0059)	(0.0057)	(0.0059)	(0.0058)	(0.0055)	(0.0033)

Six Month Options

Deciles	1	2	3	4	5	6	7	8	9	10	10-1
Returns	0.0080	0.0125**	0.0126**	0.0167***	0.0147***	0.0165***	0.0203***	0.0266***	0.0266***	0.0342***	0.0261***
St. Error	(0.005)	(0.0052)	(0.005)	(0.0052)	(0.0052)	(0.005)	(0.0053)	(0.0053)	(0.0054)	(0.0052)	(0.0032)
Sharpe Ratio	0.256	0.443	0.464	0.633	0.544	0.650	0.775	1.036	1.022	1.391	1.697

Six Minus One: Calendar Spreads

Deciles	1	2	3	4	5	6	7	8	9	10	10-1
Returns	-0.0156	0.0110	0.0278*	0.0516***	0.0487***	0.0522***	0.0660***	0.0801***	0.1026***	0.1535***	0.1690***
St. Error	0.0159	0.0155	0.0145	0.0145	0.0139	0.0140	0.0133	0.0131	0.0118	0.0109	0.0113
Sharpe Ratio	-0.254	0.127	0.397	0.769	0.755	0.806	1.085	1.339	1.920	3.123	3.312

Table 8: Straddle Returns Sorted on Change in Realized Volatility

This table reports the results of monthly straddle returns sorted on term structure and volatility subsequently realized by the underlying. Straddle returns for one, two, and six months are first sorted into quintiles based on the implied volatility term structure as measured by $\frac{1mIV}{6mIV} - 1$. Within each term structure, portfolios are then sorted into three buckets according to the change in realized volatility. The period examined spans from January, 1996, to July, 2015, and includes 924,952 straddles across all maturities and 7,076 equities.

Panel A: One Month Options Held to Expiry

	Term Structure					
ΔRV	1 (depressed)	2	3	4	5 (inverted)	5-1
1 (Low)	-0.1556***	-0.1734***	-0.1807***	-0.2040***	-0.2589***	-0.1033***
	(0.0176)	(0.0158)	(0.0154)	(0.015)	(0.0132)	(0.0103)
2	-0.0482**	-0.0751***	-0.0782***	-0.1082***	-0.1613***	-0.1131***
	(0.0190)	(0.0191)	(0.0179)	(0.0171)	(0.0159)	(0.0114)
3 (High)	0.2347***	0.1712***	0.1608***	0.1668***	0.1271***	-0.1075***
	(0.0231)	(0.0217)	(0.0222)	(0.0206)	(0.0179)	(0.0165)
3-1						-0.0042
						(0.0159)

Panel B: Two Month Options

	Term Structure					
ΔRV	1 (depressed)	2	3	4	5 (inverted)	5-1
1 (Low)	-0.0658***	-0.0657***	-0.0705***	-0.0734***	-0.0908***	-0.0249***
	(0.0177)	(0.0189)	(0.0171)	(0.0182)	(0.0171)	(0.0046)
2	-0.0115	-0.0151	-0.0103	-0.0193	-0.0327**	-0.0212***
	(0.016)	(0.016)	(0.018)	(0.015)	(0.0142)	(0.0048)
3 (High)	0.1397***	0.1245***	0.1225***	0.1394***	0.1242***	-0.0155**
	(0.0129)	(0.01)	(0.0123)	(0.0112)	(0.0091)	(0.0068)
3-1						0.0094
						(0.0065)

Panel C: Six Month Options

	Term Structure					
Δ RV	1 (depressed)	2	3	4	5 (inverted)	5-1
1 (Low)	-0.0237***	-0.0169***	-0.0189***	-0.0147***	-0.0147***	0.0090***
	(0.0044)	(0.0043)	(0.0042)	(0.0044)	(0.0043)	(0.0027)
2	-0.0010	0.0018	0.0058	0.0126**	0.0149***	0.0159***
	(0.0048)	(0.005)	(0.0051)	(0.0052)	(0.0053)	(0.0031)
3 (High)	0.0520***	0.0586***	0.0606***	0.0747***	0.0883***	0.0363***
	(0.0064)	(0.0065)	(0.0064)	(0.0068)	(0.0071)	(0.0046)
3-1						0.0273***
						(0.0050)

Table 9: Summary Statistics and Correlations: Overreaction Measures

Each month, firms are sorted according to the implied volatility term structure, as measured by $\frac{1mIV}{6mIV} - 1$. Panel A (B) lists the averages (correlations) of three overreaction measures for each term structure decile. The three measures are calculated for each firm, for each month, for each decile. Each month, the measures are averaged; the table reports the averages of the monthly averages for each decile. The first measure, $\frac{1mIV}{12mRV} - 1$, compares one month implied volatility against realized volatility calculated over one year, as defined in Goyal and Saretto. The second, VRP, measures the volatility risk premium, as defined by $\frac{1mIV}{1mRV} - 1$. The third, $\frac{1mIV}{IV_{ave}} - 1$, measures one month implied volatility against its six month average. The period examined spans from January, 1996, to July, 2015, and includes 924,952 straddles across all maturities and 7,076 equities.

Panel A: Summary Statistics

	Decile 1	2	3	4	5	6	7	8	9	Decile 10	All
$\frac{1mIV}{12mRV} - 1$	-0.1390	-0.0866	-0.0568	-0.0327	-0.0111	0.0131	0.0371	0.0723	0.1188	0.2727	0.0187
VRP	0.0690	0.0775	0.0909	0.1037	0.1119	0.1231	0.1348	0.1566	0.1907	0.3246	0.1383
$\frac{1mIV}{IV_{ave}} - 1$	-0.0100	-0.0100	-0.0094	-0.0078	-0.0069	-0.0063	-0.0050	-0.0040	-0.0020	-0.0014	-0.0063

Panel B: Correlations

	Decile 1	2	3	4	5	6	7	8	9	Decile 10	All
$\frac{1mIV}{12mRV} - 1$	0.5812	0.6193	0.6327	0.6558	0.6560	0.6575	0.6702	0.6692	0.6836	0.7474	0.6581
VRP	0.0134	0.0380	0.0934	0.1123	0.1104	0.1168	0.1215	0.1178	0.0803	0.2361	0.0183
$\frac{1mIV}{IV_{ave}} - 1$	0.5223	0.6124	0.6484	0.6575	0.6496	0.6903	0.6846	0.6920	0.7156	0.7099	0.7201

Table 10: Returns Regressed on "Underreaction", "Overreaction" Portfolios

The returns of ATM straddle portfolios created by sorting on the implied volatility term structure are regressed on "underreaction" and "overreaction" portfolios. The portfolios are sorted on the implied volatility term structure, as defined by $\frac{1mIV}{6mIV}-1$. Portfolio 1 (10) holds straddles which have the most upward-sloping (inverted) term structure. The "overreaction" and "underreaction" portfolios hold ATM straddles, and are created by sorting into deciles on $\frac{1mIV}{12mRV}-1$. The "underreaction" ("overreaction") portfolio is Decile 1 (10), where implied volatility is lowest (highest) relative to realized volatility. The final column regresses the 10-1 Portfolio, created by sorting on term structure, on the 10-1 Overreaction-Underreaction Portfolio, created by sorting on $\frac{1mIV}{12mRV}-1$. In each case below the portfolio returns are regressed on portfolios with matching maturities. The period examined spans from January, 1996, to July, 2015, and includes 924,952 straddles across all maturities and 7,076 equities.

Panel A: One Month Options Held to Expiry

Deciles	1	2	3	4	5	6	7	8	9	10	10-1
over	0.350***	0.467***	0.430***	0.450***	0.492***	0.575***	0.609***	0.610***	0.613***	0.591***	
under	0.722***	0.621***	0.596***	0.561***	0.522***	0.472***	0.394***	0.381***	0.317***	0.224***	
overunder											-0.5307***
Constant	0.0457***	0.0421***	0.0222**	0.0110	0.0157	0.0271***	0.0260**	0.0215**	-0.00342	-0.0409***	-0.0503***
R-squared	0.869	0.859	0.864	0.850	0.846	0.863	0.824	0.834	0.827	0.846	0.346

Panel B: Two Month Options Held for One Month

Deciles	1	2	3	4	5	6	7	8	9	10	10-1
over	0.342***	0.446***	0.453***	0.492***	0.447***	0.551***	0.598***	0.595***	0.648***	0.641***	
under	0.693***	0.619***	0.586***	0.536***	0.570***	0.501***	0.417***	0.413***	0.351***	0.262***	
overunder											-0.4396***
Constant	0.0026	0.0045	0.0038	0.0017	0.0000	0.0079**	0.0137***	0.0138***	0.0085**	0.0010	0.0021
R-squared	0.900	0.908	0.912	0.893	0.904	0.916	0.895	0.878	0.878	0.909	0.290

Table 10 cont.: Returns Regressed on “Underreaction”, “Overreaction” Portfolios

Panel C: Six Month Options Held for One Month

Deciles	1	2	3	4	5	6	7	8	9	10	10-1
over	0.276***	0.501***	0.504***	0.424***	0.560***	0.512***	0.462***	0.548***	0.437***	0.607***	
under	0.672***	0.499***	0.447***	0.553***	0.407***	0.434***	0.520***	0.433***	0.544***	0.382***	
overunder											-0.3044***
Constant	-0.0141***	-0.0059***	-0.0039*	-0.0025	-0.0002	0.0005	0.0025	0.0118***	0.0075**	0.0190***	0.0337***
R-squared	0.877	0.865	0.841	0.859	0.817	0.848	0.833	0.793	0.783	0.851	0.148

Table 11: Market Capitalization and Average Option Volume Traded

This table holds the time series averages of the monthly portfolio averages of market capitalization and the average notional option contract values traded for each decile, in millions of dollars. Portfolio 1 holds straddles which have the most upward sloping term structure, as defined by $\frac{1mIV}{6mIV} - 1$; Portfolio 10 holds straddles which have the most inverted term structure. The period examined spans from January, 1996, to July, 2015, and includes 924,952 straddles across all maturities and 7,076 equities.

	Decile 1	2	3	4	5	6	7	8	9	Decile 10
Size	4037	3888	3918	4093	3945	3901	4116	3984	4130	4090
Average Volume	63.8	16.2	13.5	30.0	9.2	12.2	11.9	23.3	30.1	8.2

Table 12: Option Bid-Ask Spread by Decile and Maturity

The average bid-ask spread for each maturity and decile is displayed below as a percentage of the underlying stock price. Portfolio 1 holds straddles which have the most upward sloping term structure, as defined by $\frac{1mIV}{6mIV} - 1$; Portfolio 10 holds straddles which have the most inverted term structure. The period examined spans from January, 1996, to July, 2015, and includes 924,952 straddles across all maturities and 7,076 equities.

	Decile 1	2	3	4	5	6	7	8	9	Decile 10
1m	0.76%	0.71%	0.72%	0.75%	0.77%	0.81%	0.85%	0.91%	0.98%	1.27%
2m	0.94%	0.85%	0.86%	0.90%	0.92%	0.96%	1.00%	1.08%	1.16%	1.49%
3m	0.94%	0.87%	0.89%	0.92%	0.94%	0.98%	1.01%	1.07%	1.19%	1.51%
4m	1.07%	0.96%	0.95%	1.00%	1.02%	1.09%	1.13%	1.20%	1.30%	1.66%
5m	1.13%	1.01%	1.01%	1.07%	1.10%	1.15%	1.20%	1.27%	1.38%	1.73%
6m	1.24%	1.12%	1.12%	1.15%	1.18%	1.22%	1.23%	1.37%	1.47%	1.88%

Table 13: Returns Sorted by Option Bid-Ask Spread: Effect of Transactions Costs

This table examines the impact of transactions costs on Decile 10 by presenting returns using a 0%, 50%, and 100% effective bid-ask spread. Reported below are the results of the short one month, long six month, and the one-six month calendar spread portfolio returns of Decile 10 sorted into quintiles by options bid-ask spread as a percentage of stock price: Quintile 1 has the smallest spread; Quintile 5 has the largest. The first column holds returns where the option trades are executed at the midpoint. The second column executes trades assuming the bid-ask spread is 50% as wide as the prices posted. The last column buys (sells) options on the ask (bid). The period examined spans from January, 1996, to July, 2015, and includes 924,952 straddles across all maturities and 7,076 equities.

Effective Spread		0%	50%	100%
1	1M	0.1077***	0.0923***	-0.0778***
(Narrow)	6M	0.0354***	0.0059	-0.0226
	6M - 1M	0.1415***	0.0966***	0.0534***
	Sharpe Ratio	2.17	1.47	0.80
2	1M	0.1003***	0.0729***	0.0477***
	6M	0.0267***	-0.0261	-0.0754
	6M - 1M	0.1270***	0.0499***	-0.0244
	Sharpe Ratio	2.10	0.75	-0.35
3	1M	0.1351***	0.0703***	0.0194
(Wide)	6M	0.0401***	-0.0836	-0.1835
	6M - 1M	0.1739***	-0.0146	-0.1655
	Sharpe Ratio	2.95	-0.21	-2.02

Table 14: Delta hedged Straddle Returns Sorted by Term Structure

This table reports the returns of portfolios of ATM straddles, delta hedged daily, created by sorting on the implied volatility term structure. Portfolio 1 holds straddles which have the most upward sloping term structure, as defined by $\frac{1mIV}{6mIV} - 1$; Portfolio 10 holds straddles which have the most inverted term structure. The portfolios listed contain options of one to six months maturity, held for one month. The period examined spans from January, 1996, to July, 2015, and includes 924,952 straddles across all maturities and 7,076 equities.

One Month Options

Deciles	1	2	3	4	5	6	7	8	9	10	10-1
Returns	0.0368***	0.0235**	0.0099	0.0074	-0.0056	-0.0019	-0.0023	-0.0049	-0.0305***	-0.0730***	-0.1099***
St. Error	(0.0098)	(0.0103)	(0.0089)	(0.0099)	(0.0089)	(0.0096)	(0.0113)	(0.0112)	(0.0095)	(0.0092)	(0.0063)

Two Month Options

Deciles	1	2	3	4	5	6	7	8	9	10	10-1
Returns	0.0411***	0.0407***	0.0355***	0.0350***	0.0436***	0.0384***	0.0376***	0.0393***	0.0282***	0.0174*	-0.0237***
St. Error	(0.0112)	(0.0112)	(0.0116)	(0.0108)	(0.0113)	(0.0111)	(0.0105)	(0.0111)	(0.0106)	(0.0094)	(0.0059)

Three Month Options

Deciles	1	2	3	4	5	6	7	8	9	10	10-1
Returns	0.0348***	0.0379***	0.0347***	0.0402***	0.0400***	0.0378***	0.0428***	0.0526***	0.0396***	0.0385***	0.0036
St. Error	(0.0085)	(0.0091)	(0.009)	(0.0085)	(0.0085)	(0.0089)	(0.0088)	(0.0088)	(0.0087)	(0.0082)	(0.006)

Table 14 cont.: Delta hedged Straddle Returns Sorted by Term Structure

Four Month Options

Deciles	1	2	3	4	5	6	7	8	9	10	10-1
Returns	0.0371***	0.0386***	0.0349***	0.0411***	0.0388***	0.0481***	0.0478***	0.0557***	0.0556***	0.0514***	0.0143**
St. Error	(0.0092)	(0.0099)	(0.0096)	(0.0094)	(0.0098)	(0.0098)	(0.0092)	(0.0097)	(0.0093)	(0.0092)	(0.0073)

Five Month Options

Deciles	1	2	3	4	5	6	7	8	9	10	10-1
Returns	0.0236***	0.0258***	0.0409***	0.0444***	0.0538***	0.0491***	0.0581***	0.0649***	0.0611***	0.0713***	0.0476***
St. Error	(0.0093)	(0.0094)	(0.0095)	(0.0108)	(0.0101)	(0.0093)	(0.0105)	(0.0099)	(0.0092)	(0.0096)	(0.0079)

Six Month Options

Deciles	1	2	3	4	5	6	7	8	9	10	10-1
Returns	0.0250***	0.0348***	0.0373***	0.0486***	0.0355***	0.0459***	0.0368***	0.0533***	0.0507***	0.0659***	0.0410***
St. Error	(0.0086)	(0.009)	(0.0086)	(0.0087)	(0.0085)	(0.0084)	(0.0086)	(0.0079)	(0.009)	(0.0087)	(0.0076)

Table 15: Straddle Returns Separated by Upcoming Earnings Release, Sorted by Term Structure

This table reports the portfolio returns of one month, two month, and six month ATM straddles separated into two groups based on whether the firm will be releasing an earnings statement over the next option expiration cycle. Each group is then sorted by term structure. Portfolio 1 holds straddles which have the most upward sloping term structure, as defined by $\frac{1mIV}{6mIV} - 1$; Portfolio 10 holds straddles which have the most inverted term structure. The period examined spans from January, 1996, to July, 2015, and includes 924,952 straddles across all maturities and 7,076 equities.

No Earnings Release Within Next Expiration Cycle

One Month Options

Deciles	1	2	3	4	5	6	7	8	9	10	10-1
Returns	0.0107***	-0.0146***	-0.0265	-0.0489***	-0.0589***	-0.0602***	-0.0776***	-0.0800***	-0.0927***	-0.1576***	-0.1683***
St. Error	(0.0208)	(0.0193)	(0.0203)	(0.0196)	(0.019)	(0.0183)	(0.0182)	(0.0195)	(0.0169)	(0.0161)	(0.0147)

Two Month Options

Deciles	1	2	3	4	5	6	7	8	9	10	10-1
Returns	0.0248**	0.0203*	0.0177*	0.0122	0.0106	0.0185*	0.0171*	0.0161*	0.0080	-0.0056	-0.0304***
St. Error	(0.0108)	(0.0106)	(0.0105)	(0.0101)	(0.0102)	(0.0102)	(0.0099)	(0.0098)	(0.0093)	(0.0082)	(0.0064)

Six Month Options

Deciles	1	2	3	4	5	6	7	8	9	10	10-1
Returns	0.0069	0.0109**	0.0140***	0.0151***	0.0140***	0.0174***	0.0206***	0.0350***	0.0297***	0.0358***	0.0289***
St. Error	(0.0055)	(0.0054)	(0.0054)	(0.0054)	(0.0053)	(0.0053)	(0.0056)	(0.0086)	(0.0056)	(0.0055)	(0.0042)

Table 15 cont.: Straddle Returns Separated by Upcoming Earnings Release, Sorted by Term Structure

Earnings Release Within Next Expiration Cycle

One Month Options

Deciles	1	2	3	4	5	6	7	8	9	10	10-1
Returns	0.1844***	0.1192***	0.0952***	0.0112	0.0481*	0.0570**	0.0340	0.0044	-0.0243	-0.0644***	-0.2474***
St. Error	(0.036)	(0.0354)	(0.0339)	(0.0234)	(0.0293)	(0.0268)	(0.023)	(0.0191)	(0.0177)	(0.015)	(0.0364)

Two Month Options

Deciles	1	2	3	4	5	6	7	8	9	10	10-1
Returns	0.0274***	0.0149	0.0199*	0.0209*	0.0046	-0.0007	0.0158	0.0076	0.0054	0.0049	-0.0245**
St. Error	(0.0112)	(0.0114)	(0.0116)	(0.0121)	(0.0107)	(0.011)	(0.0125)	(0.0137)	(0.0121)	(0.0138)	(0.0124)

Six Month Options

Deciles	1	2	3	4	5	6	7	8	9	10	10-1
Returns	0.0101*	0.0146**	0.0072	0.0128*	0.0088	0.0031	0.0092	0.0115*	0.0150**	0.0325***	0.0219***
St. Error	(0.0062)	(0.0064)	(0.0063)	(0.0067)	(0.007)	(0.0058)	(0.0067)	(0.0063)	(0.0076)	(0.0066)	(0.0065)

Table 16: Variance Swaps: Summary Statistics

Each month, equally weighted portfolios of hypothetical variance swaps (VS) are formed based on the difference between the one month variance swap rate and the one month variance swap rate one month forward, defined as $\frac{VS(1)}{FV(1,1)} - 1$. Portfolio 1 (10) holds VS whose current one month variance swap rate is lowest (highest) relative to the one month VS one month forward, FV(1,1). The first stanza of the table holds the current/forward differential, $\frac{VS(1)}{FV(1,1)} - 1$; one and two month VS rates, $VS(1)$ and $VS(2)$; and the first differences of each expressed as a percentage, $\Delta VX(1)$ and $\Delta VX(2)$; the one month VS one month forward, $FV(1,1)$; and the t+1 one month VS rate, $VS_{t+1}(1)$. The second stanza holds the equivalent levels for volatility swaps for ease of analysis. All volatility and variance measures are represented in volatility and variance "points", as defined by $Volatility * 100$ and $Variance * 10000$. The period examined spans from January, 1996, to July, 2015, and includes 56,932 straddles and 2,977 equities.

	Decile 1	2	3	4	5	6	7	8	9	Decile 10	All
$\frac{VS(1)}{FV(1,1)} - 1$	-0.3296	-0.1945	-0.1224	-0.0623	-0.0085	0.0480	0.1152	0.2048	0.3559	0.9688	0.0975
$VS(1)$	2753.84	2806.23	2809.55	3058.26	3042.15	3354.34	3438.89	3564.35	3982.79	4818.16	3362.86
$\Delta VX(1)$	-0.1096	-0.0696	-0.0710	-0.0076	-0.0257	0.0608	0.0955	0.0637	0.1456	0.4063	0.0488
$VS(2)$	3422.11	3085.11	2958.57	3107.03	3011.00	3231.93	3222.61	3240.28	3435.82	3743.04	3245.75
$\Delta VX(2)$	0.1423	0.0602	0.0120	0.0468	0.0113	0.0660	0.0634	0.0028	0.0148	0.0810	0.0501
$FV(1,1)$	4049.92	3358.43	3106.45	3163.26	2991.95	3129.85	3033.03	2949.12	2944.09	2763.87	3149.00
$VS_{t+1}(1)$	3642.89	3282.32	3125.34	3256.40	3153.62	3273.49	3330.87	3323.39	3458.12	3636.85	3348.33

Volatility Swaps

	Decile 1	2	3	4	5	6	7	8	9	Decile 10	All
$\frac{1mVolSwap}{FV(1,1)} - 1$	-0.1878	-0.1064	-0.0669	-0.0354	-0.0081	0.0197	0.0517	0.0926	0.1580	0.3524	0.0270
1m Vol Swap	47.34	47.66	47.97	49.77	49.96	52.22	53.03	54.38	57.63	63.92	52.39
2m Vol Swap	53.23	50.41	49.57	50.51	50.01	51.55	51.59	52.02	53.70	56.43	51.90
1m Vol Swap 1m fwd	58.06	52.85	51.02	51.20	50.05	50.92	50.22	49.72	49.78	48.30	51.21
1m Vol Swap, t+1	54.83	51.75	50.60	51.41	50.73	51.63	52.01	52.04	53.16	54.42	52.26
N	5583	5705	5733	5702	5683	5747	5730	5705	5733	5611	56932

Table 17: Variance Swaps: Predictive Regressions

Each month, equally weighted portfolios of hypothetical variance swaps (VS) are formed based on the difference between the one month variance swap rate and the one month variance swap rate one month forward, defined as $\frac{VS(1)}{FV(1,1)} - 1$. Portfolio 1 (10) holds VS whose current one month variance swap rate is lowest (highest) relative to the one month VS one month forward. This table contains the results of the predictive regression $VS_{t+1}(1) = \alpha + \beta * FV(1,1) + \epsilon_{t+1}$, for the ten portfolios. The period examined spans from January, 1996, to July, 2015, and includes 56,932 straddles and 2,977 equities.

	Decile 1	2	3	4	5	6	7	8	9	10	All
α	0.0155	0.0307**	0.0070	0.0091	0.0008	0.0269**	0.0225	-0.0076	0.0029	-0.0024	-0.0040
	(0.0155)	(0.0140)	(0.0127)	(0.0131)	(0.0138)	(0.0125)	0.0143)	(0.0131)	(0.0145)	(0.0156)	(0.0137)
β	0.8612***	0.8861***	0.9835	1.0006	1.0513	0.9600	1.0240	1.1527***	1.1649***	1.3245***	1.0769**
	(0.0339)	(0.0360)	(0.0353)	(0.0352)	(0.0392)	(0.0330)	(0.0398)	(0.0377)	(0.0422)	(0.0486)	(0.0383)
t-stat ($\beta = 1$)	4.0938	3.1672	0.4670	-0.0164	-1.3085	1.2152	-0.6035	-4.0542	-3.9108	-6.6811	-2.0067
R^2	0.7356	0.7234	0.7695	0.7767	0.7560	0.7853	0.7405	0.8014	0.7669	0.7623	0.7730

Table 18: Returns of Variance Swaps

Each month, equally weighted portfolios of hypothetical variance swaps (VS) are formed based on the difference between the one month variance swap rate and the one month variance swap rate one month forward, defined as $\frac{VS(1)}{FV(1,1)} - 1$. Portfolio 1 (10) holds VS whose current one month variance swap rate is lowest (highest) relative to the one month VS one month forward. This table contains the time series average portfolio returns, standard deviations, (t)-statistics for portfolios 1 through 10, and the Long/Short 10-1 portfolio. In addition, the annualized Sharpe Ratio is included for the 10-1 portfolio. The period examined spans from January, 1996, to July, 2015, and includes 56,932 straddles and 2,977 equities.

	Decile 1	2	3	4	5	6	7	8	9	Decile 10	10-1
Return	-0.0557	0.0032	0.0217	0.0532	0.0686	0.0756	0.1185	0.1343	0.1967	0.4968	0.5525
St. Error	(0.0180)	(0.0219)	(0.0216)	(0.0230)	(0.0239)	(0.0232)	(0.0241)	(0.0238)	(0.0272)	(0.0747)	(0.0675)
t-stat	-3.09	0.14	1.00	2.31	2.87	3.26	4.92	5.63	7.22	6.65	8.18
Sharpe Ratio											1.85

Table 19: Summary Statistics of Calendar Spreads

Each month, portfolios of calendar spreads are formed based on the implied volatility differential between the two legs, as defined by $\frac{1mIV}{FV(1,1)} - 1$. The calendar spreads consist of a long two month ATM equity option straddle and a short one month ATM equity option straddle. Portfolio 1 (10) holds calendar spreads whose implied volatility curves have steepest upward (downward) slope. The period examined spans from January, 1996, to July, 2015, and includes 284,984 calendar spreads and 6,799 equities.

	Decile 1	2	3	4	5	6	7	8	9	10	All
$\frac{1mIV}{FV(1,1)} - 1$	-0.2038	-0.1083	-0.0665	-0.0346	-0.0058	0.0230	0.0558	0.0974	0.1630	0.4157	0.0417
1m IV	0.3928	0.4038	0.4168	0.4259	0.4364	0.4441	0.4570	0.4681	0.4863	0.5289	0.4425
2m IV	0.4488	0.4280	0.4307	0.4325	0.4366	0.4382	0.4441	0.4469	0.4525	0.4594	0.4374
FV(1,1)	0.4942	0.4494	0.4433	0.4385	0.4368	0.4325	0.4318	0.4261	0.4185	0.3853	0.4305
Delta	0.0050	0.0030	0.0046	0.0056	0.0067	0.0064	0.0070	0.0076	0.0071	0.0064	0.0035
N	28387	28519	28527	28516	28482	28560	28527	28516	28530	28420	284984

Table 20: Returns of Calendar Spreads

Each month, portfolios of calendar spreads are formed based on the implied volatility differential between the two legs, as defined by $\frac{1mIV}{FV(1,1)} - 1$. The calendar spreads consist of a long two month ATM equity option straddle and a short one month ATM equity option straddle. Portfolio 1 (10) holds calendar spreads whose implied volatility curves have steepest upward (downward) slope. The spreads are constructed such that the notional amounts of the one month and two month options are equal. The period examined spans from January, 1996, to July, 2015, and includes 284,984 calendar spreads and 6,799 equities.

	Decile 1	2	3	4	5	6	7	8	9	Decile 10	‘10-1
1m Straddle Ret.	-0.0369***	-0.0550***	-0.0594***	-0.0617***	-0.0679***	-0.0758***	-0.0797***	-0.0925***	-0.1011***	-0.1390***	
2m Straddle Ret.	-0.0220***	-0.0178**	-0.0147	-0.0113	-0.0113	-0.0122	-0.0082	-0.0134	-0.0093	-0.0197***	
Cal. Spread Ret.	0.0425***	0.0919***	0.1122***	0.1374***	0.1588***	0.1790***	0.2143***	0.2475***	0.3135***	0.5277***	0.4852***
St. Error	(0.0087)	(0.0096)	(0.0101)	(0.0113)	(0.0121)	(0.0117)	(0.0125)	(0.0127)	(0.0138)	(0.0169)	(0.0154)
Sharpe Ratio	1.11	2.17	2.52	2.75	2.96	3.46	3.86	4.41	5.13	7.05	7.12

Table 21: Calendar Spreads: Returns with Transactions Costs

Each month, portfolios of calendar spreads are formed based on the implied volatility differential between the two legs, as defined by $\frac{1mIV}{FV(1,1)} - 1$. The calendar spreads consist of a long two month ATM equity option straddle and a short one month ATM equity option straddle. The spreads are constructed such that the notional amounts of the one month and two month options are equal. Portfolio 1 (5) holds calendar spreads whose implied volatility curves have steepest upward (downward) slope. The portfolios are sorted again according to the bid-ask spread of the one month options. The returns shown are calculated using an effective bid-ask spread of 50% that which is quoted. The period examined spans from January, 1996, to July, 2015, and includes 284,984 calendar spreads and 6,799 equities.

			Term Structure			
Spread	1	2	3	4	5	5-1
1	-0.0663	-0.0363	-0.0036	0.0293***	0.0965***	-0.0705
	(0.0131)	(0.0124)	(0.0136)	(0.0134)	(0.0157)	(0.0197)
Sharpe Ratio	-1.15	-0.66	-0.06	0.49	1.39	-0.80
2	-0.1239	-0.0942	-0.0757	-0.0455	0.0228	-0.2493
	(0.010)	(0.0103)	(0.0114)	(0.0128)	(0.0161)	(0.0164)
3	-0.1708	-0.1490	-0.1173	-0.0846	-0.0450	-0.4229
	(0.0096)	(0.0103)	(0.0117)	(0.0120)	(0.0139)	(0.0186)
4	-0.2266	-0.1985	-0.1809	-0.1593	-0.1018	-0.7108
	(0.0092)	(0.0103)	(0.0117)	(0.0123)	(0.0155)	(0.0292)
5	-0.3480	-0.3004	-0.2813	-0.2703	-0.2402	-1.7678
	(0.0106)	(0.0128)	(0.0128)	(0.0142)	(0.0166)	(0.0746)

Table 22: Calendar Spreads: Earnings Announcements

Each month, portfolios of calendar spreads are formed based on the implied volatility differential between the two legs, as defined by $\frac{1mIV}{FV(1,1)} - 1$. The calendar spreads consist of a long two month ATM equity option straddle and a short one month ATM equity option straddle. Portfolio 1 (5) holds calendar spreads whose implied volatility curves have steepest upward (downward) slope. The spreads are constructed such that the notional amounts of the one month and two month options are equal. The sample is split into two sub-samples based on whether the underlying firm releases an earnings announcement over the holding period. The period examined spans from January, 1996 to August, 2015, and includes 284,984 calendar spreads and 6,799 equities.

			Term Structure			
	1	2	3	4	5	5-1
Earnings	0.0047	0.0903***	0.1076***	0.1865***	0.3329***	0.3444***
	(0.0174)	(0.0242)	(0.0213)	(0.0175)	(0.0185)	(0.0213)
N	9958	13596	16555	19270	24906	
Sharpe Ratio						3.65
No Earnings	0.0761***	0.1482***	0.1941***	0.2688***	0.5081***	0.4358***
	(0.0090)	(0.0116)	(0.0119)	(0.0128)	(0.0213)	(0.0204)
N	46948	43447	40487	37773	32044	
Sharpe Ratio						4.82
Earnings -						-0.0972***
No Earnings 5-1						(0.0283)
Sharpe Ratio						-0.79

Table 23: Calendar Spreads: Returns Conditioned on Equity Volume

Each month, portfolios of calendar spreads are formed based on the implied volatility differential between the two legs, as defined by $\frac{1mIV}{FV(1,1)} - 1$. The calendar spreads consist of a long two month ATM equity option straddle and a short one month ATM equity option straddle. Portfolio 1 (5) holds calendar spreads whose implied volatility curves have steepest upward (downward) slope. The portfolios are then sorted on the basis of average daily equity volume traded expressed as a percentage of market capitalization. The 5-1 Portfolios own Portfolio 5 and short Portfolio 1 each month. The 1-5, 5-1 Portfolio buys the 5-1 Portfolio in Volume Quintile 1 and sells the 5-1 Portfolio in Volume Quintile 5. The spreads are constructed such that the notional amounts of the one month and two month options are equal. The period examined spans from January, 1996 to August, 2015, and includes 284,984 calendar spreads and 6,799 equities.

			Term Structure			
Volume	1	2	3	4	5	5-1
1	0.0887	0.1388	0.1967	0.2583	0.4887	0.4000
St. Error	(0.0123)	(0.0120)	(0.0130)	(0.0162)	(0.0201)	(0.0202)
Sharpe Ratio						4.48
2	0.0859	0.1436	0.1674	0.2416	0.4651	0.3792
St. Error	(0.0114)	(0.0130)	(0.0143)	(0.0146)	(0.0197)	(0.0194)
Sharpe Ratio						4.41
3	0.0601	0.1352	0.1673	0.2282	0.4069	0.3468
St. Error	(0.0112)	(0.0137)	(0.0142)	(0.0151)	(0.0193)	(0.0183)
Sharpe Ratio						4.28
4	0.0619	0.1270	0.1566	0.2315	0.3903	0.3284
St. Error	(0.0106)	(0.0152)	(0.0139)	(0.0169)	(0.0176)	(0.0169)
Sharpe Ratio						4.39
5	0.0409	0.0815	0.1563	0.1988	0.3402	0.2993
St. Error	(0.0103)	(0.0122)	(0.0168)	(0.0149)	(0.0173)	(0.0168)
Sharpe Ratio						4.02
1-5						0.1006***
St. Error						(0.0256)
Sharpe Ratio						0.89

Table 24: Calendar Spreads: Returns Conditioned on Market Capitalization

Each month, portfolios of calendar spreads are formed based on the implied volatility differential between the two legs, as defined by $\frac{1mIV}{FV(1,1)} - 1$. The calendar spreads consist of a long two month ATM equity option straddle and a short one month ATM equity option straddle. Portfolio 1 (5) holds calendar spreads whose implied volatility curves have steepest upward (downward) slope. The portfolios are then sorted on the basis of firm market capitalization, calculated as the average market capitalization calculated daily over the preceding month. The 1-5, 5-1 Portfolio buys the 5-1 Portfolio in Size Quintile 1 and sells the 5-1 Portfolio in Size Quintile 5. The spreads are constructed such that the notional amounts of the one month and two month options are equal. The period examined spans from January, 1996 to August, 2015, and includes 284,984 calendar spreads and 6,799 equities.

			Term Structure			
Mkt Cap	1	2	3	4	5	5-1
1	0.0835***	0.1579***	0.2061***	0.2701***	0.5133***	0.4299***
St. Error	(0.0110)	(0.0116)	(0.0129)	(0.0134)	(0.0202)	(0.0191)
Sharpe Ratio						5.09
2	0.0750***	0.1288***	0.1697***	0.2370***	0.4262***	0.3512***
St. Error	(0.0117)	(0.0137)	(0.0124)	(0.0139)	(0.0170)	(0.0169)
Sharpe Ratio						4.70
3	0.0592***	0.1051***	0.1668***	0.2180***	0.4142***	0.3550***
St. Error	(0.0111)	(0.0116)	(0.0138)	(0.0150)	(0.0186)	(0.0163)
Sharpe Ratio						4.94
4	0.0556***	0.1124***	0.1615***	0.2168***	0.3653***	0.3096***
St. Error	(0.0112)	(0.0131)	(0.0185)	(0.0158)	(0.0195)	(0.0181)
Sharpe Ratio						3.86
5	0.0613***	0.1261***	0.1440***	0.2134***	0.3454***	0.2842***
St. Error	(0.0124)	(0.0158)	(0.0145)	(0.0167)	(0.0238)	(0.0235)
Sharpe Ratio						2.73
1-5						0.1457***
St. Error						(0.0274)
Sharpe Ratio						1.20

Table 25: Returns of Deferred Calendar Spreads

Each month, portfolios of calendar spreads are formed based on the implied volatility differential between the two legs. The two calendar spreads examined are a two month four month calendar spread (2m-4m return) and a three month six month calendar spread (3m-6m return). Portfolio 1 (10) holds calendar spreads whose implied volatility curves have steepest upward (downward) slope. The spreads are constructed such that the notional amounts of the short and long term options are equal. The period examined spans from January, 1996, to July, 2015. The two month four month calendar spread sample includes 129,779 calendar spreads and 6,912 equities; the three month six month calendar spread includes 138,064 calendar spreads and 7,022 equities.

	Decile 1	2	3	4	5	6	7	8	9	Decile 10	10-1
2m-4m Return	0.0759***	0.1024***	0.1196***	0.1250***	0.1553***	0.1844***	0.1907***	0.2112***	0.2668***	0.4556***	0.3733***
St. Error	(0.0049)	(0.0067)	(0.0078)	(0.0082)	(0.0101)	(0.0120)	(0.0124)	(0.0138)	(0.0174)	(0.0297)	(0.0244)
Sharpe Ratio											3.16
3m-6m Return	0.0790***	0.1175***	0.1600***	0.1565***	0.1841***	0.2018***	0.2237***	0.2535***	0.3140***	0.5045***	0.4254***
St. Error	(0.0052)	(0.0077)	(0.0104)	(0.0102)	(0.0120)	(0.0132)	(0.0146)	(0.0165)	(0.0205)	(0.0329)	(0.0278)
Sharpe Ratio											2.65

Table 26: Carry: Summary Statistics and Correlations Across Assets

This table contains the summary statistics and correlations for long-short carry returns across assets. The long-short carry strategies here represent the carry1-12 strategy in Koijen, Moskowitz, Pedersen, and Vrugt (2013), and the data used here was obtained from Lasse H. Pedersen's website. EQ represents global equities; FL-LVL represents global bond levels; FL-SLP represents global bond slope; FX represents foreign exchange; COM represents commodities; TR represents United States Treasuries; CR represents credit; OC represent S&P 500 index call options; and OC represent S&P 500 index put options. The sample used here extends from January, 1996 to September, 2012.

Summary Statistics

	EQ	FI-LVL	FI-SLP	FX	COM	TR	CR	OC	OP
Mean	0.0015	0.0024	0.0001	0.0042	0.0094	0.0001	0.0002	0.0355	0.1134
St. Dev.	0.0273	0.0124	0.0015	0.0222	0.0519	0.0012	0.0020	0.4584	0.2580
SR	0.19	0.66	0.28	0.66	0.63	0.31	0.28	0.26	1.52

Correlations

	EQ	FI-LVL	FI-SLP	FX	COM	TR	CR	OC	OP
FI-LVL	0.175								
FI-SLP	0.218	-0.130							
FX	0.131	0.328	0.198						
COM	0.027	-0.010	0.089	0.199					
TR	0.158	0.373	0.093	0.087	0.014				
CR	0.125	-0.119	0.081	0.385	0.267	0.082			
OC	0.074	0.050	-0.013	-0.050	-0.141	0.064	-0.045		
OP	-0.002	0.036	0.161	0.155	0.147	0.132	0.099	0.224	
EqVolCarry	0.009	0.025	-0.146	-0.124	-0.067	-0.030	-0.175	-0.171	-0.133

Table 27: Exposures of Long-Short Equity Volatility Carry Portfolio

This table holds the results of regressing the Long-Short Equity Volatility Carry Portfolio on the excess returns of the market (Mkt-RF), small minus big portfolio returns (SMB), high minus low portfolio returns (HML), momentum portfolio returns (MOM), traded liquidity portfolio returns (Liq) as per Pástor and Stambaugh (2003), zero beta straddle returns (zbr) of Coval and Shumway (2001), and the Diversified Carry portfolio returns (DCarry) of Koijen, Moskowitz, Pedersen, and Vrugt (2013). The excess market, SMB, HML, and MOM returns are obtained from the website of Kenneth French; the Liq returns are obtained from the website of Lubos Pastor; the DCarry returns are obtained from the website of Lasse Pedersen. The period examined spans from 1996 through September, 2012.

	(1) EqVolCarry	(2) EqVolCarry	(3) EqVolCarry	(4) EqVolCarry
MktRF	-1.329***	-1.604***	-1.564***	-1.493***
	(-4.38)	(-4.85)	(-4.68)	(-4.20)
SMB		0.353	0.392	0.266
		(0.72)	(0.80)	(0.51)
HML		-0.863	-0.890	-0.970
		(-1.78)	(-1.83)	(-1.91)
MOM		-0.460	-0.440	-0.363
		(-1.44)	(-1.37)	(-1.10)
Liq			-0.362	-0.441
			(-0.88)	(-1.00)
zbr				0.00743
				(0.29)
DCarry				1.126
				(0.83)
cons	0.493***	0.499***	0.501***	0.509***
	(33.01)	(32.83)	(32.62)	(29.24)

t statistics in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 28: Exposures of Equity Long Volatility Carry Portfolio

This table holds the results of regressing the Equity Long Volatility Carry Portfolio, after accounting for transactions costs, on the excess returns of the market (Mkt-RF), small minus big portfolio returns (SMB), high minus low portfolio returns (HML), momentum portfolio returns (MOM), traded liquidity portfolio returns (Liq) as per Pástor and Stambaugh (2003), zero beta straddle returns (zbr) of Coval and Shumway (2001), and the Diversified Carry portfolio returns (DCarry) of Koijen, Moskowitz, Pedersen, and Vrugt (2013). The excess market, SMB, HML, and MOM returns are obtained from the website of Kenneth French; the Liq returns are obtained from the website of Lubos Pastor; the DCarry returns are obtained from the website of Lasse Pedersen. The period examined spans from 1996 through September, 2012.

	(1)	(2)	(3)	(4)
	LongCarry	LongCarry	LongCarry	LongCarry
MktRF	-1.666***	-1.909***	-1.987***	-2.061***
	(-5.55)	(-5.82)	(-6.02)	(-6.10)
SMB		0.265	0.190	-0.337
		(0.55)	(0.39)	(-0.68)
HML		-0.406	-0.355	-0.726
		(-0.85)	(-0.74)	(-1.51)
MOM		-0.577	-0.615	-0.419
		(-1.82)	(-1.94)	(-1.33)
Liq			0.694	0.0272
			(1.71)	(0.06)
zbr				-0.108***
				(-4.52)
DCarry				0.966
				(0.75)
_cons	0.105***	0.110***	0.107***	0.120***
	(7.10)	(7.31)	(7.04)	(7.27)

t statistics in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 29: Covered Call Summary Statistics: Monthly Returns, 1996 - 2015

This table reports the summary statistics of the S&P 500 Index, the covered call strategy and the hedged covered call strategy of Israelov and Nielsen (2015). The sample period runs from 1996-2015, and monthly statistics are calculated over the standard monthly expiration periods. The covered call and hedged covered call strategies sell a one month ATM call each month and cash settle the option. The hedged covered call strategy delta hedges the call daily so that the combined delta of the position is 0.50.

	S&P 500 Index	Covered Call	Hedged Covered Call
Monthly Return	0.0075	0.0066	0.0065
Standard Deviation	0.0493	0.0339	0.0284
Skew	-0.97	-1.99	-1.32
Kurtosis	6.37	11.49	7.83
Minimum	-0.2138	-0.1882	-0.1380
Maximum	0.1773	0.1455	0.1005
Ann. Sharpe Ratio	0.39	0.47	0.57
Beta	1.00	0.60	0.56
Upside Beta	1.00	0.39	0.55
Downside Beta	1.00	0.77	0.58

Table 30: Decomposition of Covered Call Strategies: 1996 - 2015

This table decomposes the covered call and hedged covered call strategies. Panel A decomposes the ATM covered call strategy into its two components: the S&P 500 Index position and short one month ATM call sold each month. Panel B decomposes the ATM hedged covered call strategy into an S&P 500 Index position equal to 50% of the portfolio, and a short one month ATM S&P 500 Index call, delta hedged daily. The sample period runs from 1996-2015, and monthly statistics are calculated over the standard monthly expiration periods.

Panel A

	S&P 500 Index	Short ATM Call	Covered Call
Monthly Return	0.0075	-0.0010	0.0066
Standard Deviation	0.0493	0.0261	0.0339
Skew	-0.97	-0.91	-1.99
Kurtosis	6.37	3.96	11.49
Minimum	-0.2138	-0.1016	-0.1882
Maximum	0.1773	0.0738	0.1455
Ann. Sharpe Ratio	0.39	-0.15	0.47
Beta	1.00	-0.42	0.60
Upside Beta	1.00	-0.62	0.39
Downside Beta	1.00	-0.25	0.77

Panel B

	S&P 500 Index Position (50%)	Short Delta Hedged ATM Call	Hedged Covered Call
Monthly Return	0.0038	0.0027	0.0065
Standard Deviation	0.0247	0.0060	0.0284
Skew	-0.97	-0.85	-1.32
Kurtosis	6.37	6.29	7.83
Minimum	-0.1069	-0.0276	-0.1380
Maximum	0.0887	0.0180	0.1005
Ann. Sharpe Ratio	0.39	1.55	0.57
Beta	1.00	0.05	0.56
Upside Beta	1.00	0.03	0.55
Downside Beta	1.00	0.06	0.58

Table 31: Summary Statistics of Volatility Exposures: 2007 - 2015

This table contains the monthly return summary statistics of short S&P 500 Index volatility exposures from the period 2007 through 2015. Monthly statistics are calculated over the standard monthly expiration periods. The first column is the short ATM S&P 500 Index call position, delta hedged daily. The second column refers to a short position in the constant maturity one month VIX future, obtaining by partially rolling the position daily to maintain the constant maturity.

	Short Delta Hedged ATM Call	Short Constant Maturity VIX Future
Monthly Return	0.0510	0.0293
Standard Deviation	0.2616	0.1983
Skew	-0.95	-2.10
Kurtosis	4.40	9.24
Minimum	-0.8500	-0.9674
Maximum	0.7127	0.2829
Ann. Sharpe Ratio	0.68	0.51
Beta	2.43	2.38
Upside Beta	1.05	0.29
Downside Beta	2.58	3.83
Correlation		0.69

Table 32: Conditional Returns: Volatility Exposures, 2007 - 2015

This table contains the monthly return summary statistics of three short S&P 500 Index volatility exposures from the period 2007 through 2015, conditional on the VIX term structure slope. Monthly statistics are calculated over the standard monthly expiration periods. The first column is the short ATM S&P 500 Index call position, delta hedged daily. The second column refers to a short position in the constant maturity one month VIX future, obtaining by partially rolling the position daily to maintain the constant maturity. For each, the position is held as long as the slope of the VIX term structure is positive, as measured by the difference between the VIX Index and the constant one month VIX Future.

	Short Delta Hedged ATM Call	Short Constant Maturity VIX Future
Monthly Return	0.0310	0.0428
Standard Deviation	0.2480	0.1273
Skew	-0.63	-0.55
Kurtosis	3.97	3.44
Minimum	-0.7700	-0.3321
Maximum	0.7127	0.2877
Ann. Sharpe Ratio	0.43	1.16

Table 33: Volatility/Equity Portfolio Returns

The table contains the summary statistics from 2007 through 2015 of the S&P 500 Index, the covered call and hedged covered call strategies, and a portfolio holding the S&P 500 Index and a short position in the constant maturity one month VIX future. The portfolio holding VIX futures and the S&P 500 Index are weighted such that each month, 50% of the portfolio is invested in the S&P 500 Index and the vega of the VIX futures position is equal to the vega of the one month ATM call sold in the covered call strategies. The sample is divided into two panels: Panel A holds the unconditional returns; Panel B holds the returns conditional on the sign of term structure slope. For each, the position is held as long as the slope of the VIX term structure is positive, as measured by the difference between the VIX Index and the constant one month VIX Future.

Panel A: Unconditional Returns

	S&P 500 Index	Covered Call	Hedged Covered Call	S&P 500 + Constant 1M VIX
Monthly Return	0.0067	0.0045	0.0047	0.0041
Standard Deviation	0.0556	0.0397	0.0327	0.0319
Skew	-1.07	-1.68	-1.42	-1.57
Kurtosis	6.48	10.09	7.76	8.19
Minimum	-0.2137	-0.1882	-0.1380	-0.1357
Maximum	0.1773	0.1455	0.1005	0.0911
Ann. Sharpe Ratio	0.42	0.39	0.50	0.45
Beta	1.00	0.65	0.58	0.57
Upside Beta	1.00	0.38	0.53	0.51
Downside Beta	1.00	0.88	0.63	0.63

Panel B: Conditional Returns

	S&P 500 Index	Covered Call	Hedged Covered Call	S&P 500 + Constant 1M VIX
Monthly Return	0.0067	0.0056	0.0043	0.0045
Standard Deviation	0.0556	0.0516	0.0304	0.0290
Skew	-1.07	-0.98	-1.02	-1.05
Kurtosis	6.48	12.39	6.11	5.83
Minimum	-0.2137	-0.2207	-0.1104	-0.1069
Maximum	0.1773	0.2425	0.0992	0.0882
Ann. Sharpe Ratio	0.42	0.38	0.49	0.54
Beta	1.00	0.84	0.54	0.52
Upside Beta	1.00	0.71	0.53	0.51
Downside Beta	1.00	1.10	0.53	0.51

Table 34: Volatility/Equity Portfolios: Fixed Allocations

The table contains the summary statistics from 2007 through 2015 of the S&P 500 Index and a portfolio holding the S&P 500 Index and a short position in the constant maturity one month VIX future. The VIX futures/S&P 500 Index portfolio is constructed so that 50% of the portfolio is invested in the S&P 500 Index and 2%, 5%, or 10% is allocated to the short VIX futures position. The sample is divided into two panels: Panel A holds the unconditional returns; Panel B holds the returns conditional on the term structure slope. For each, the position is held as long as the slope of the VIX term structure is positive, as measured by the difference between the VIX Index and the constant one month VIX Future.

Panel A: Unconditional Returns

	S&P 500 Index	50% S&P 500 2% VIX	50% S&P 500 5% VIX	50% S&P 500 10% VIX
Monthly Return	0.0067	0.0039	0.0048	0.0063
Standard Deviation	0.0556	0.0305	0.0352	0.0436
Skew	-1.07	-1.34	-1.63	-1.05
Kurtosis	6.48	7.03	7.77	8.62
Minimum	-0.2137	-0.1262	-0.1553	-0.2036
Maximum	0.1773	0.0894	0.0906	0.0925
Ann. Sharpe Ratio	0.42	0.45	0.47	0.50
Beta	1.00	0.55	0.62	0.74
Upside Beta	1.00	0.51	0.51	0.53
Downside Beta	1.00	0.58	0.69	0.88

Panel B: Conditional Returns

	S&P 500 Index	50% S&P 500 2% VIX	50% S&P 500 5% VIX	50% S&P 500 10% VIX
Monthly Return	0.0067	0.0042	0.0055	0.0076
Standard Deviation	0.0556	0.0289	0.0308	0.0347
Skew	-1.07	-1.05	-1.00	-0.90
Kurtosis	6.48	5.89	5.10	4.14
Minimum	-0.2137	-0.1069	-0.1069	-0.1069
Maximum	0.1773	0.0885	0.0883	0.0879
Ann. Sharpe Ratio	0.42	0.50	0.62	0.75
Beta	1.00	0.52	0.54	0.59
Upside Beta	1.00	0.50	0.51	0.52
Downside Beta	1.00	0.51	0.52	0.54

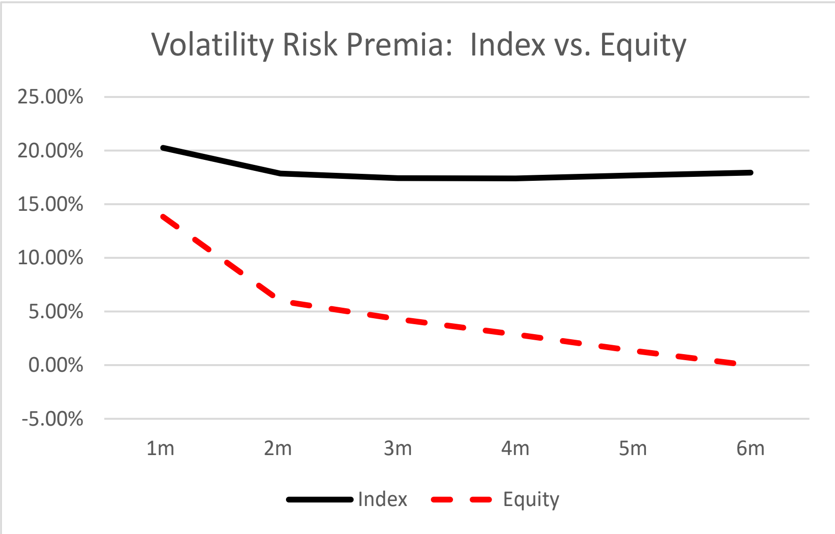
Table 35: Volatility/Equity Portfolios: Variable Allocations

The table contains the summary statistics from 2007 through 2015 of the Optimized Portfolio holding the S&P 500 Index and a constant maturity one month VIX future, optimized by maximizing the expected Sharpe Ratio where the expected return of the index is set to a long term historical average of S&P 500 Index returns; the expected return of the VIX futures is the basis; and the expected variances and covariance use the daily returns of the prior month. The Volatility Targeted Optimized Portfolio adjusts the portfolio allocations of the Optimized Portfolio so the expected return volatility equals the expected volatility of the S&P 500 Index. The index and hedged covered call is included for comparison purposes.

	S&P 500 Index	Hedged Covered Call	Optimized Portfolio	Volatility Targeted Optimized Portfolio
Monthly Return	0.0067	0.0047	0.0501	0.0202
Standard Deviation	0.0556	0.0327	0.1409	0.0595
Skew	-1.07	-1.42	0.00	-1.15
Kurtosis	6.48	7.76	3.21	8.41
Minimum	-0.2137	-0.1380	-0.2963	-0.2585
Maximum	0.1773	0.1005	0.4893	0.2187
Ann. Sharpe Ratio	0.42	0.50	1.23	1.18
Beta	1.00	0.58	1.80	0.95
Upside Beta	1.00	0.53	2.13	1.06
Downside Beta	1.00	0.63	1.33	0.89

Figure 1: Term Structure of Volatility Risk Premia

The top figure plots the time series averages of the portfolio averages of realized and implied volatilites for the Quintile 1 and 5 portfolios. Each month, we place ATM straddles into five portfolios according to the implied volatility term structure. The bottom figure sorts the S&P 500 Index *ex post* on term structure over the sample period. In each case, Portfolio 1 holds straddles which have the most upward sloping term structure, as defined by $\frac{1mIV}{6mIV} - 1$; Portfolio 5 holds straddles which have the most inverted term structure. The period examined spans from January, 1996, to July, 2015, and includes 924,952 straddles across all maturities and 7,076 equities.



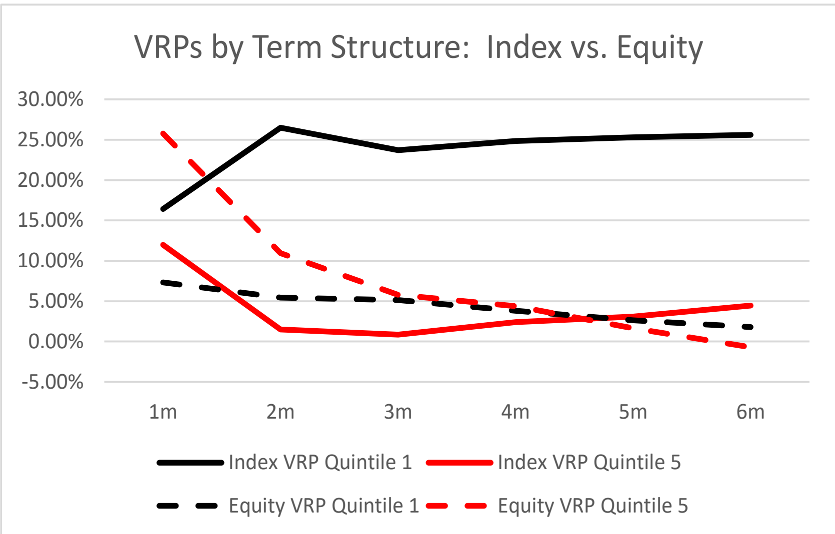


Figure 2: Time Series of Implied Volatilities

This figure plots the time series of the average one month and six month implied volatilities, and the one-six month implied volatility spread, for the Decile 1 and 10 portfolios. Each month, ATM straddles are placed into ten portfolios according to the implied volatility term structure. Portfolio 1 holds straddles which have the most upward sloping term structure, as defined by $\frac{1mIV}{6mIV} - 1$; Portfolio 10 holds straddles which have the most inverted term structure. The period examined spans from January, 1996, to July, 2015, and includes 924,952 straddles across all maturities and 7,076 equities.

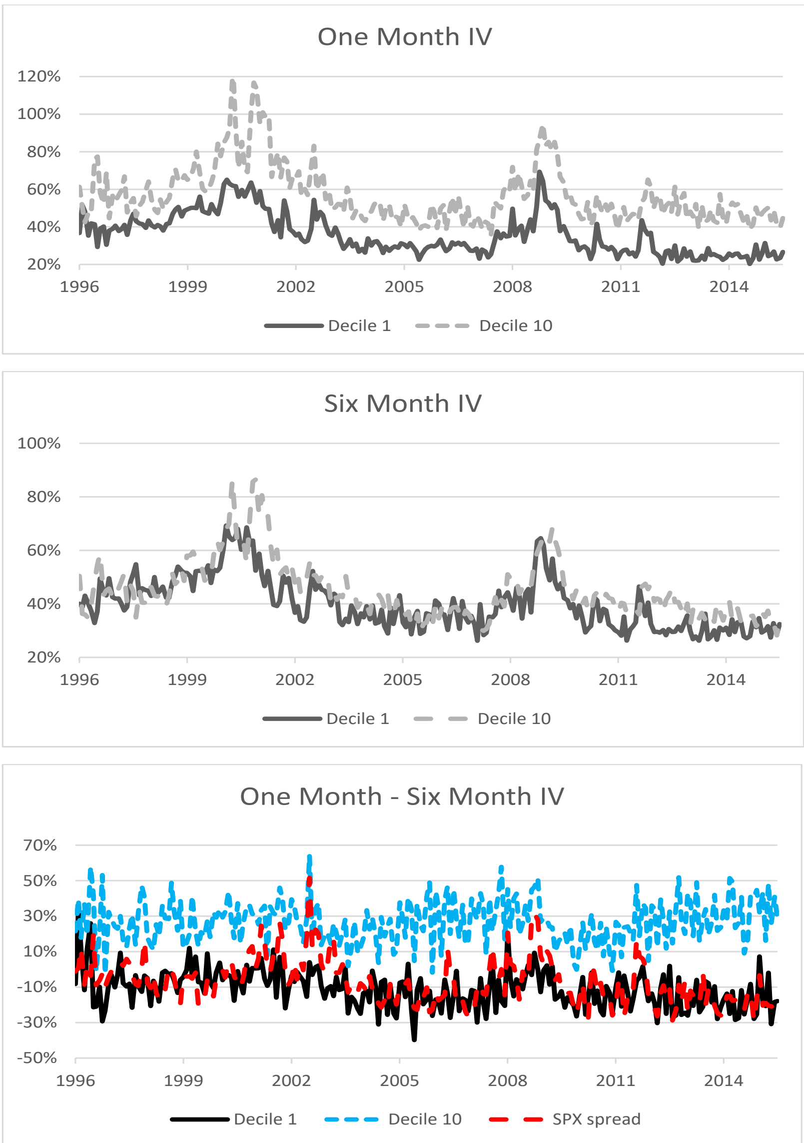


Figure 3: Time Series of Monthly Returns

The figure below plots the monthly time series of returns for three long/short options portfolios. Each month, ATM straddles are placed into ten portfolios according to the implied volatility term structure. Portfolio 1 holds straddles which have the most upward sloping term structure, as defined by $\frac{1mIV}{6mIV} - 1$; Portfolio 10 holds straddles which have the most inverted term structure. The three portfolios in this figure own Portfolio 10 and short Portfolio 1 for one, two, and six month options. The period examined spans from January, 1996, to July, 2015, and includes 924,952 straddles across all maturities and 7,076 equities.

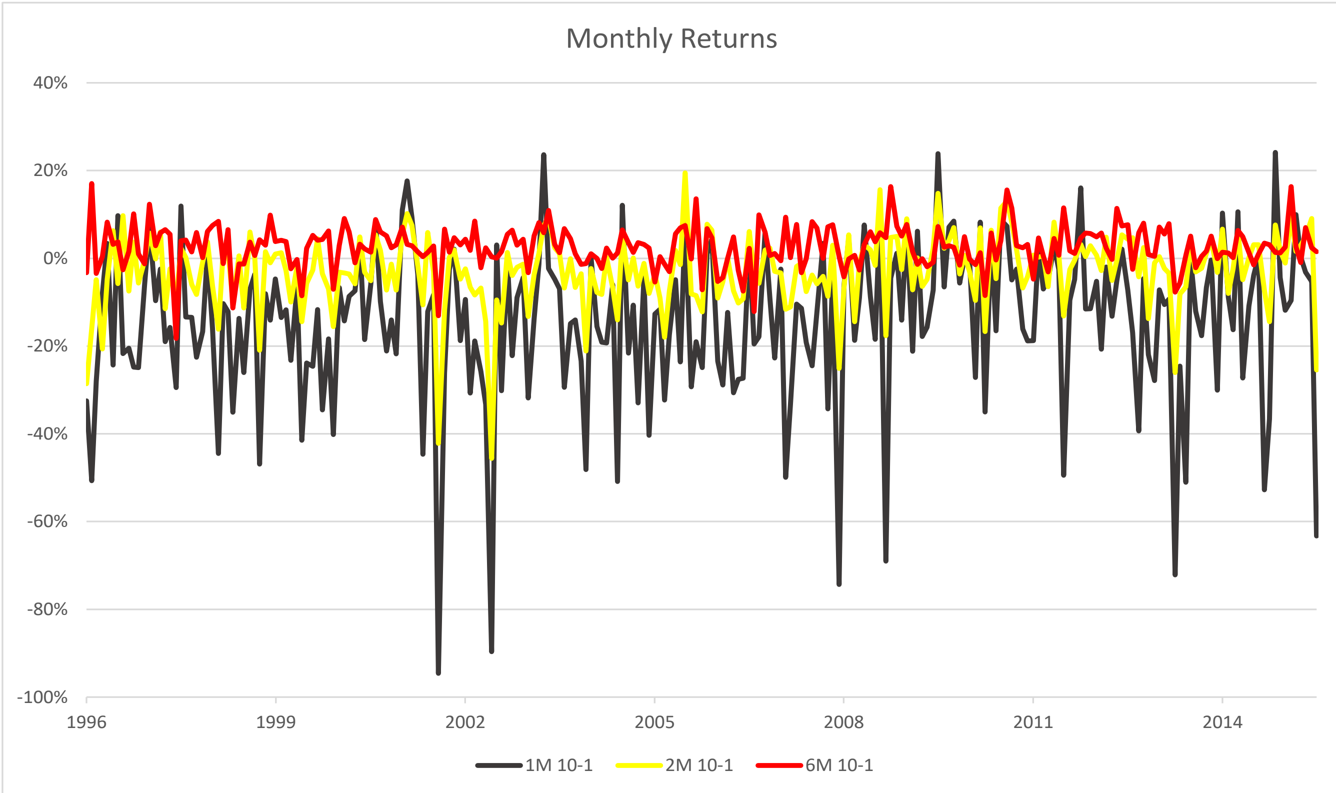


Figure 4: Variance Swap and Forward Variance Swap Levels by Decile

This figure plots the time series average of the one month variance swap and FV(1,1) levels for the ten portfolios created each month by sorting on $\frac{VS(1)}{FV(1,1)} - 1$. The period examined spans from January, 1996, to July, 2015, and includes 2,977 equities and 56,932 variance swaps.

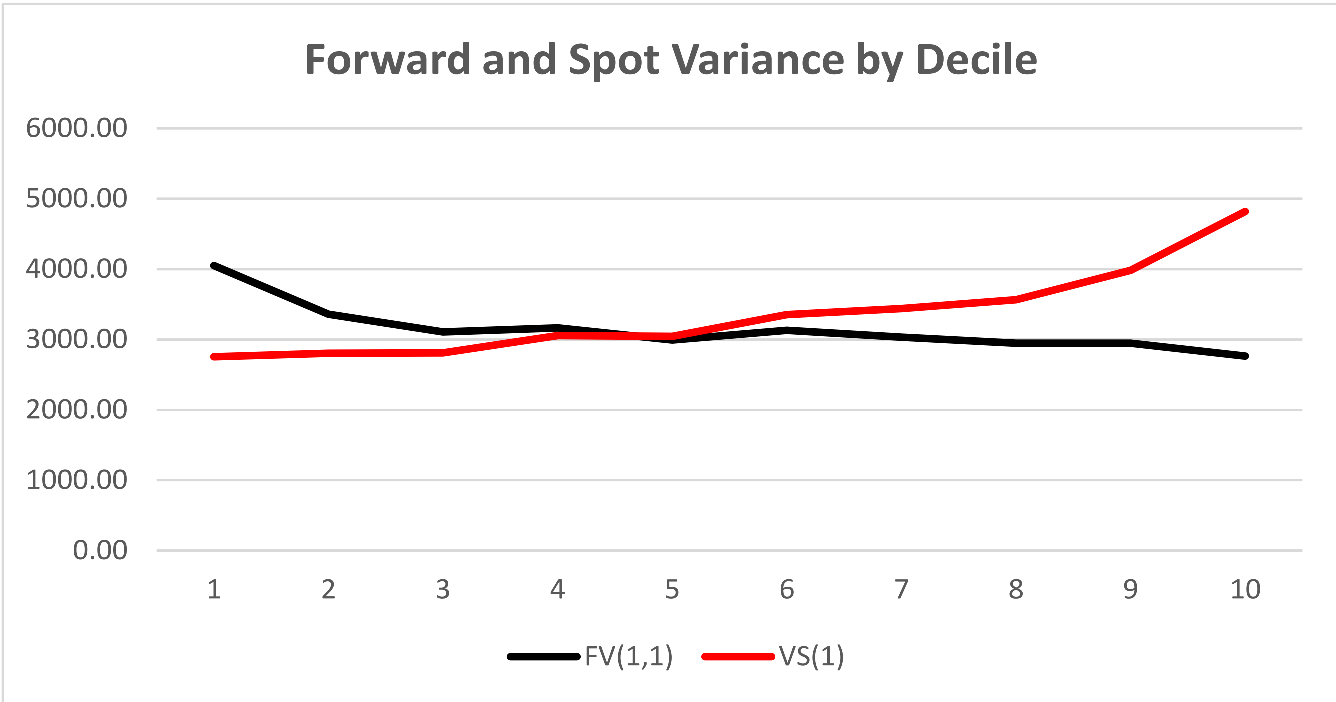


Figure 5: Current, Future Variance Swap and Forward Variance Swap Levels by Decile

This figure plots the time series average of the one month variance swap, t+1 one month variance swap, and FV(1,1) levels for the ten portfolios created each month by sorting on $\frac{VS(1)}{FV(1,1)} - 1$. The period examined spans from January, 1996, to July, 2015, and includes 2,977 equities and 56,932 variance swaps.

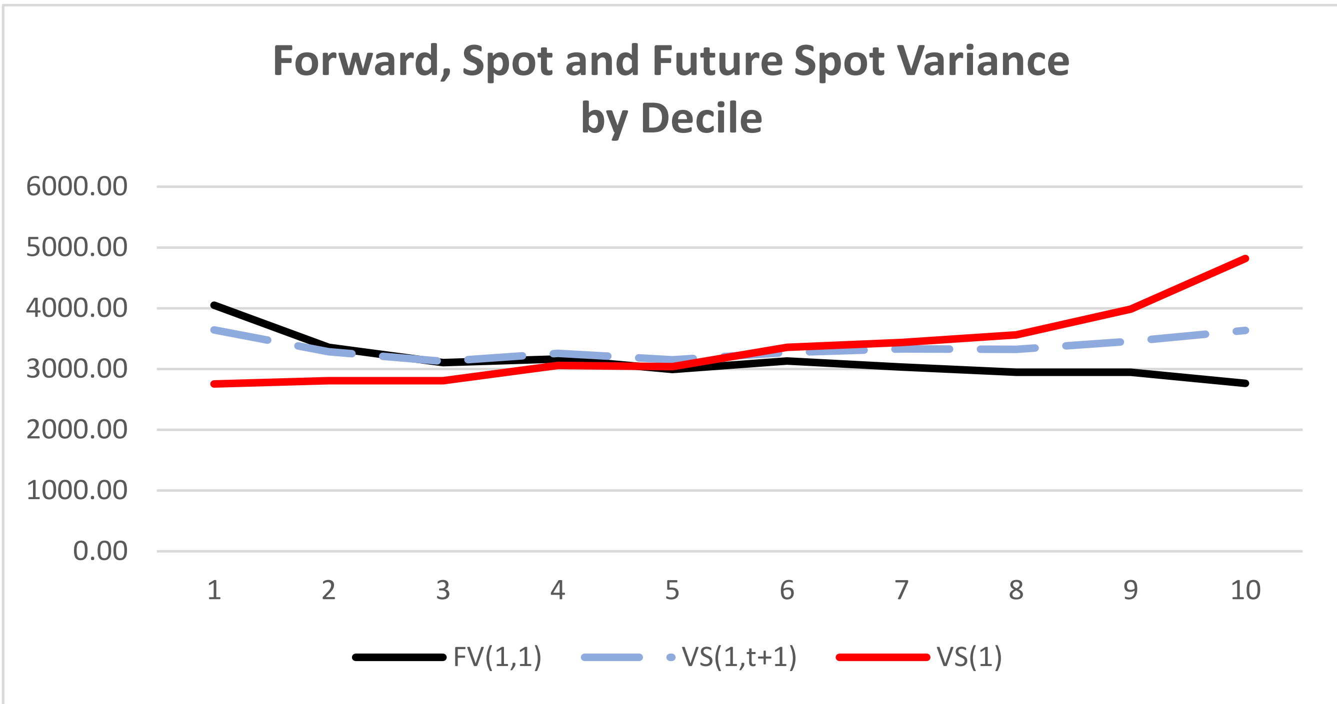


Figure 6: Returns to Equity Volatility Carry Trades

This figure contains the value of a portfolio investing in the equity volatility carry strategy implemented through variance swaps and ATM straddles and the returns to the S&P 500 Index. Each portfolio begins with $1. Due to the large monthly returns as compared to the S&P 500 Index, 1% of the portfolio is invested in each carry strategy.

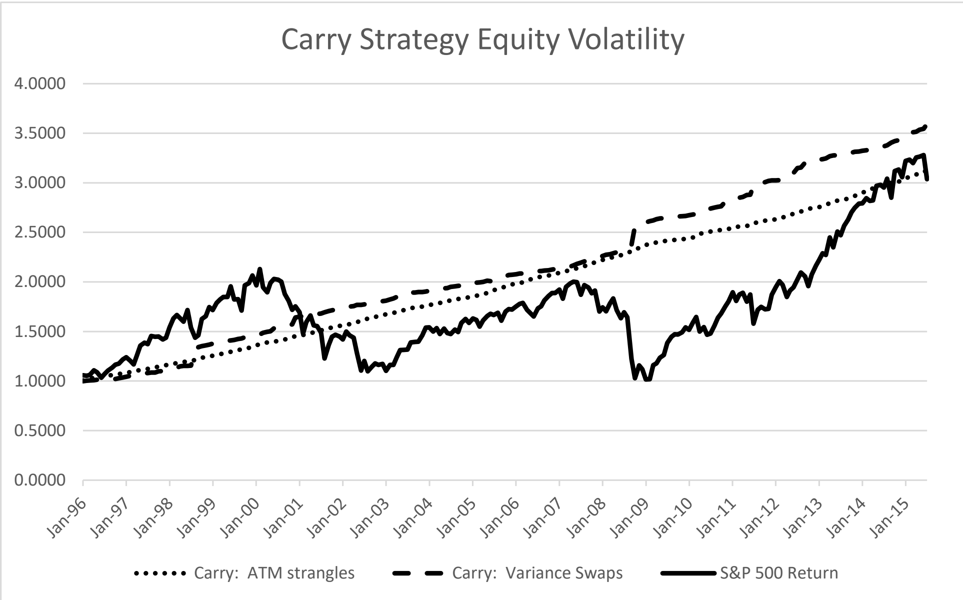


Figure 7: Returns to Long Volatility Carry Trade

This figure contains the value of a portfolio investing in the S&P 500 Index and a long volatility carry strategy after accounting for transactions costs. Each month calendar spreads are sorted into quintiles based on both term structure slope and bid-ask spread. The long volatility carry portfolio holds calendar spreads in the tightest bid-ask spread quintile and lowest (most inverted) term structure slope quintile. Each portfolio begins with $1. Due to the large monthly returns as compared to the S&P 500 Index, 5% of the portfolio is invested in each carry strategy.

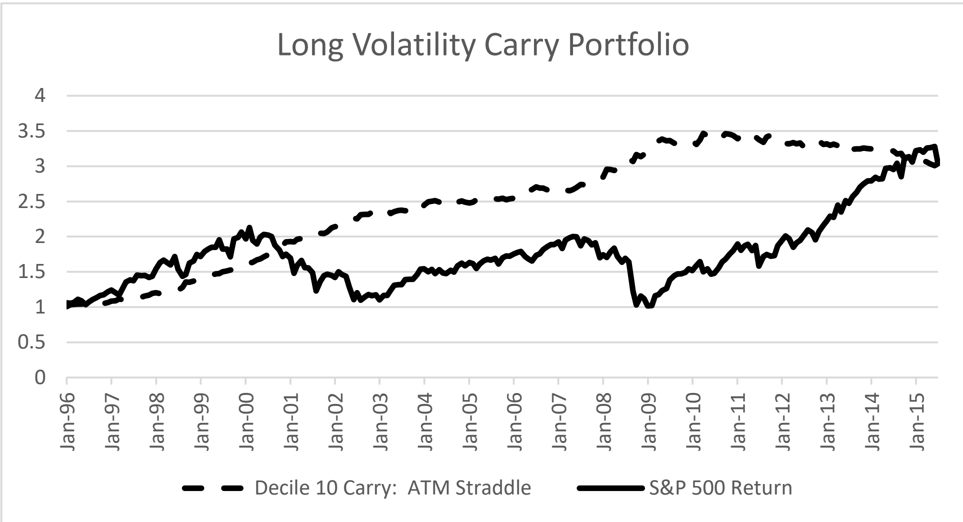


Figure 8: Composition of Term Structure Slope Portfolios

Each month, portfolios of calendar spreads are formed based on the implied volatility differential between the two legs, as defined by $\frac{1mIV}{FV(1,1)} - 1$. Portfolio 1 (5) holds variance swaps whose implied volatility curves have steepest upward (downward) slope. This figure shows the average percentage composition of each portfolio for firms with and without an upcoming earnings release. The period examined spans from January, 1996, to August, 2015, and includes 284,984 calendar spreads and 6,799 equities.

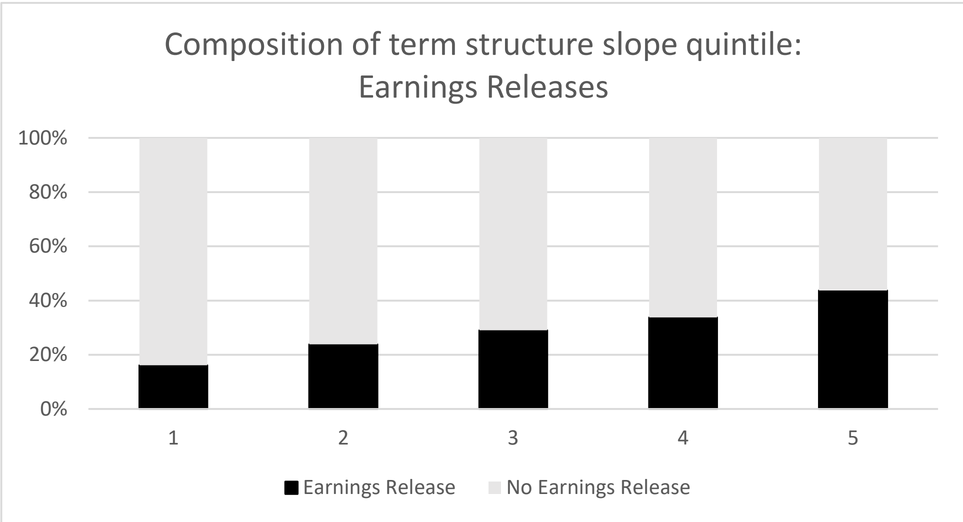


Figure 9: Returns to Carry Trades

This figure contains the value of a portfolio investing in the carry strategy implemented through variance swaps and ATM straddles, a diversified carry portfolio as per Koijen, Moskowitz, Pedersen, and Vrugt (2013), and the returns to the S&P 500 Index. Each portfolio begins with $1. Due to the large monthly returns as compared to the S&P 500 Index, 1% of the portfolio is invested in each carry strategy.

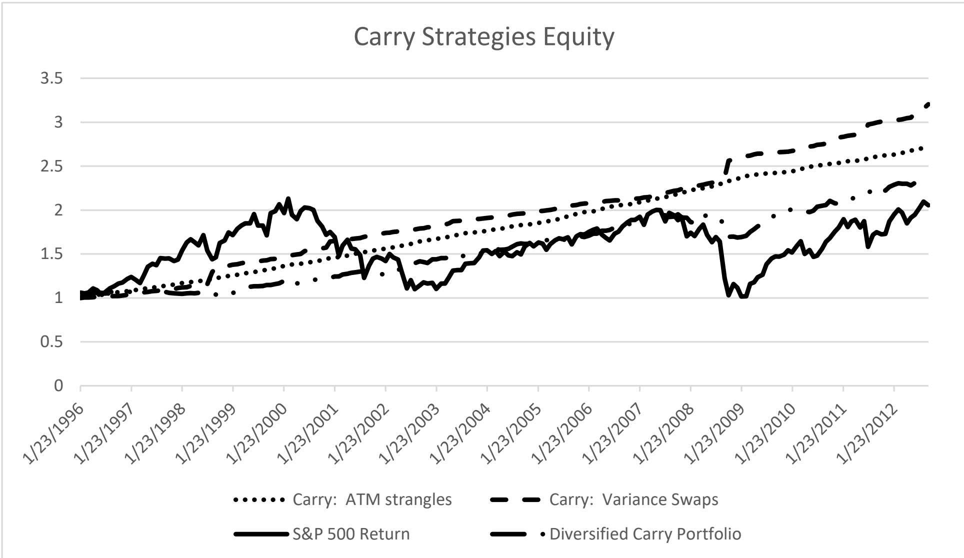


Figure 10: Returns to Long Volatility Carry Trade

This figure contains the value of a portfolio investing in the Quintile 5 Slope/Quintile 1 Spread carry strategy implemented using ATM straddles after accounting for transactions costs, a diversified carry portfolio as per Koijen, Moskowitz, Pedersen, and Vrugt (2013), and the returns to the S&P 500 Index. Each portfolio begins with $1. Due to the large monthly returns as compared to the S&P 500 Index, 5% of the portfolio is invested in each carry strategy.

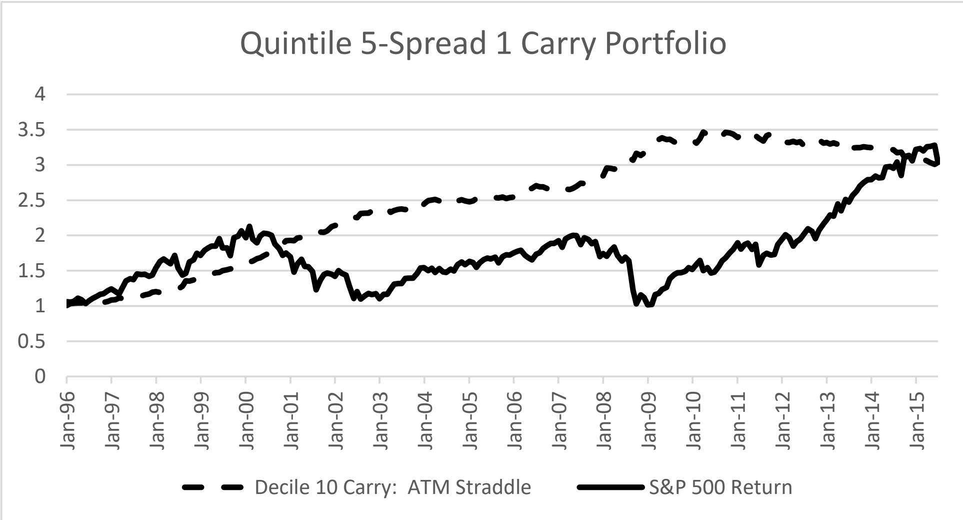


Figure 11: VIX Futures Beta with respect to VIX Index

This figure plots the beta of the front month VIX futures contract with respect to the VIX Index as a function of the days until expiration. The period examined spans from 2007 through 2015.

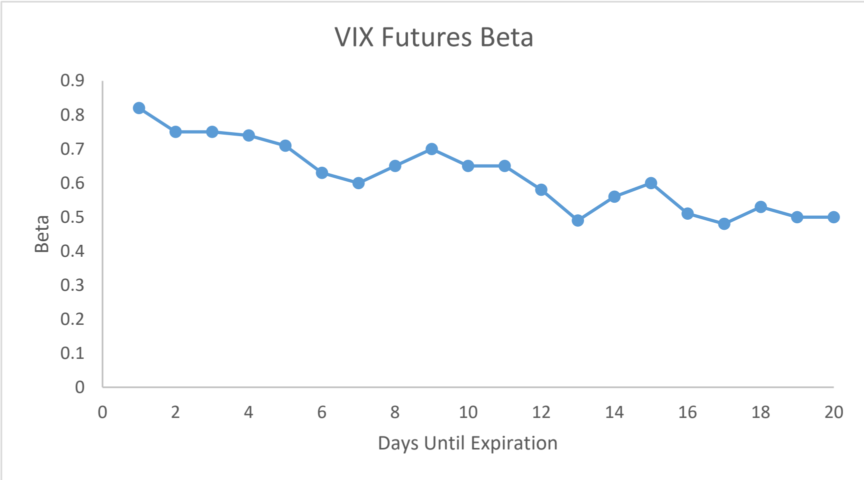


Figure 12: VIX Futures Allocation, Fully Allocated Portfolio

This figure plots the VIX Futures allocation of the Optimized Portfolio created by maximizing the expected Sharpe Ratio where the expected return of the index is set to a long term historical average of S&P 500 Index returns; the expected return of the VIX futures is the basis; and the expected variances and covariance use the daily returns of the prior month. The period examined spans from 2007 through 2015.

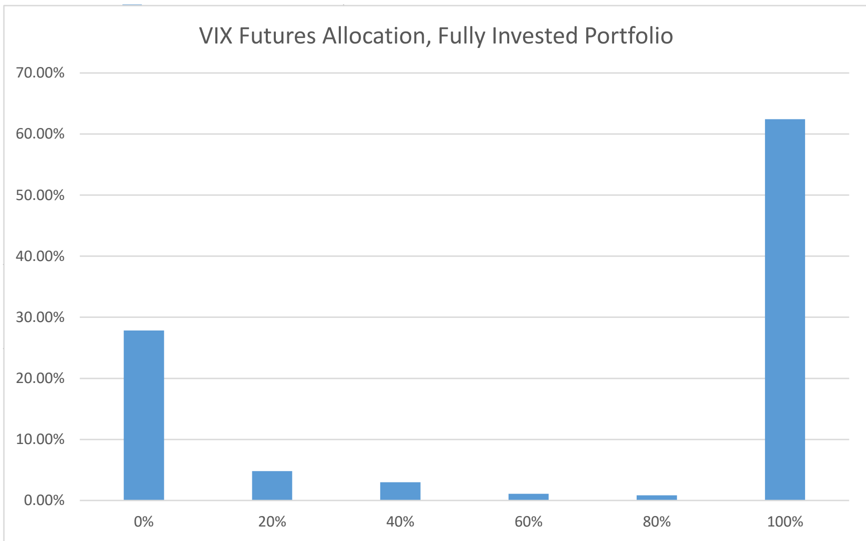
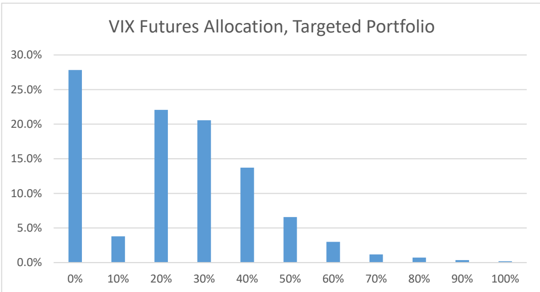
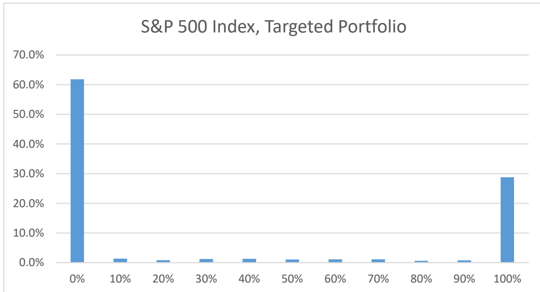


Figure 13: Allocations, Volatility Targeted Optimized Portfolio

This figure plots the VIX Futures, S&P 500 Index, and cash allocations of the Volatility Targeted Optimized Portfolio created by maximizing the expected Sharpe Ratio where the expected return of the index is set to a long term historical average of S&P 500 Index returns; the expected return of the VIX futures is the basis; and the expected variances and covariance use the daily returns of the prior month. The portfolio then adjusts allocations so the expected return volatility equals the expected volatility of the S&P 500 Index. The period examined spans from 2007 through 2015.





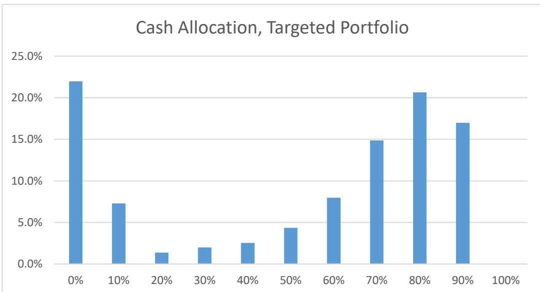
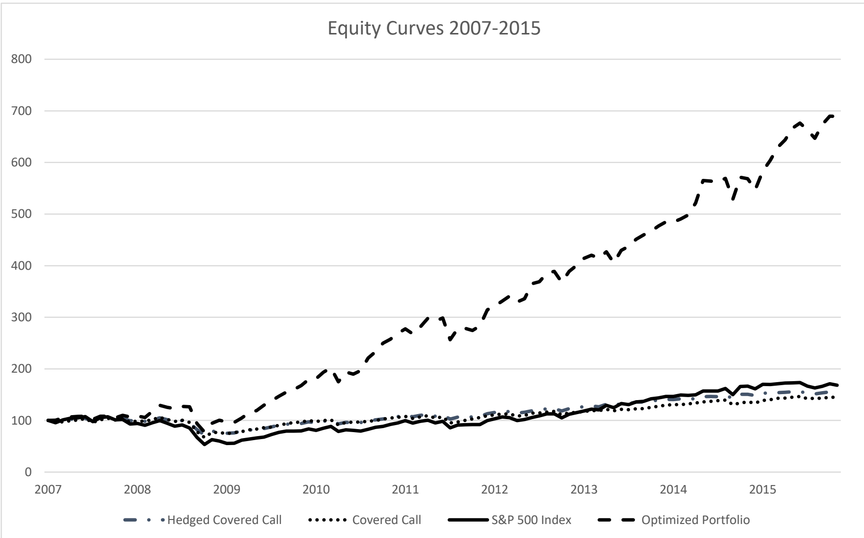


Figure 14: Equity Curves, 2007-2015

This figure plots the equity curves of the S&P 500 Index, an ATM Covered Call, a hedged ATM Covered Call, and a portfolio created by maximizing the expected Sharpe Ratio where the expected return of the index is set to a long term historical average of S&P 500 Index returns; the expected return of the VIX futures is the basis; and the expected variances and covariance use the daily returns of the prior month. The portfolio then adjusts the portfolio allocations so the expected return volatility equals the expected volatility of the S&P 500 Index. The period examined spans from 2007 through 2015.



APPENDIX

RECENT RETURNS TO OPTIMIZED PORTFOLIO

On February 6, 2018, XIV, an exchange traded note that tracks the inverse of the constant maturity VIX futures, opened more than 90% lower than the previous close. Credit Suisse, the issuer of the product, subsequently liquidated the note on February 21st. The episode received widespread media coverage, as volatility products were cited as the trigger for the broader market sell-off.[8] Table A1 holds the returns of the Optimized Portfolio and the Volatility Targeted Optimized Portfolio from 2016 through February 13, 2018. The Optimized Portfolio allocates to the constant maturity VIX future and S&P 500 Index, optimized *ex ante* using historical measures of return volatility, index returns, and the VIX futures basis. The Volatility Targeted Optimized Portfolio allocates to the Optimized Portfolio and cash in order to target the return volatility of the S&P 500 Index. Over the period, the index saw steady positive returns which produced a Sharpe Ratio of 1.58. The Volatility Targeted Optimized Portfolio posted a substantially similar return, volatility and Sharpe Ratio to the S&P 500 Index. From December, 2017 through 2018, the S&P 500 Index returned approximately 1.2%, while the Volatility Targeted Optimized Portfolio returned 0.4%. During the volatility spike in early February, the Volatility Targeted Optimized Portfolio allocated entirely to the index, as the expected returns to the VIX futures position were negative.

[8]See for example, Reklaitis (2018): https://www.marketwatch.com/story/credit-suisse-ceo-defends-enabling-bets-against-volatility-with-xiv-it-worked-well-for-a-long-time-until-it-didnt-2018-02-14.

Table A1: Volatility/Equity Portfolios: Results 2016 to February 2018

The table contains the summary statistics from 2016 through February 13, 2018 of the Optimized Portfolio holding the S&P 500 Index and a constant maturity one month VIX future, optimized by maximizing the expected Sharpe Ratio where the expected return of the index is set to a long term historical average of S&P 500 Index returns; the expected return of the VIX futures is the basis; and the expected variances and covariance use the daily returns of the prior month. The Volatility Targeted Optimized Portfolio adjusts the portfolio allocations of the Optimized Portfolio so the expected return volatility equals the expected volatility of the S&P 500 Index. The S&P 500 Index is included for comparison purposes.

	S&P 500 Index	Optimized Portfolio	Volatility Targeted Optimized Portfolio
Monthly Return	0.0123	0.0561	0.0123
Standard Deviation	0.0269	0.1301	0.0273
Skew	-0.57	0.68	-0.37
Kurtosis	4.16	3.94	4.74
Minimum	-0.0561	-0.2187	-0.0506
Maximum	0.0678	0.3809	0.0826
Ann. Sharpe Ratio	1.58	1.49	1.56

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