Contingent Claims and Hedging of Credit Risk with Equity Options

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Abstract

We derive theoretical hedge ratios of credit spreads to equity options based on the structural credit risk model of Merton (1974) and the compound option pricing model of Geske (1979). We empirically test the model hedge ratios on a sample of North American firms for which both credit default swaps (CDS) and equity options are available. Our results show that these contingent claim models generate accurate predictions of the sensitivity of CDS spread changes to changes in the value of equity options. Interestingly, relative to hedge ratios estimated empirically from the observed sensitivity of credit spreads to option returns, our model hedge ratios improve hedging effectiveness both in terms of in-sample fit (adjusted R-squared values of 7 percentage points higher) and volatility reduction (15% lower out-of-sample for the entire portfolio of firms). Our findings are relevant for credit risk managers: the hedging approach we propose aims at offsetting losses in the market value of a long credit risk position. As a result, it is a more efficient alternative to methods adopted by practitioners which are based on hedging default losses subject to substantial recovery risk.

JEL classification: E43, E44, G10

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I Introduction

Since the publication of the seminal paper by Modigliani and Miller (1958) on the theory of optimal capital structure, extensive attention has been drawn on the relationship between debt and equity values. Based on the option pricing theory developed by Black and Scholes (1973), Merton (1974) introduced the first structural model of credit risk showing how equity and debt can be valued using contingent-claims analysis. According to Merton, a debt claim is equivalent to a long position in a risk-free bond and a short position on a put option on the firm's asset value. Similarly, an equity claim is equivalent to a call option on the firm value. Among the other assumptions, his model assumes a diffusion-type stochastic process for the dynamics of the firm value and that default occurs when the firm value falls below a default threshold (which is a function of debt).[1] A few years later, using option pricing theory, Geske (1979) developed a structural model to price options on options (or compound options). If a stock can be seen as a call option on the value of the firm, an option on the stock is equivalent to an option on an option.

In this paper, we combine the structural models of Merton (1974) and Geske (1979) to study the sensitivities of credit spreads to equity options. The main contribution of this article is twofold. First, we derive theoretical hedge ratios of credit spreads to equity options using the contingent-claims valuation approach. In particular, we analytically solve the partial derivative of the credit spread with respect to the option price using the credit spread implied by Merton (1974)'s model as well as the option price implied by Geske (1979)'s model. We multiply this partial derivative by the model option price to obtain the final hedge ratio. While previous studies have analyzed the ability of Merton (1974)'s model to generate accurate sensitivities of debt to equity values (Schaefer and Strebulaev, 2008), we are the

[1] Since Merton (1974), structural models of credit risk have evolved to include stochastic interest rates (Longstaff and Schwartz, 1995), stochastic jump-diffusion process for the firm value (Cremers *et al.*, 2008b), dynamic capital structure (Leland, 1994; Leland and Toft, 1996), stationary leverage ratios (Collin-Dufresne and Goldstein, 2001) and strategic default (Anderson and Sundaresan, 1996; Anderson *et al.*, 1996; Mella-Barral and Perraudin, 1997). More recent models have attempted to incorporate macroeconomic conditions to explain credit spreads (David, 2008; Chen *et al.*, 2009; Chen, 2010; Bhamra, 2010).

first to test whether the compound option model of Geske (1979) produces accurate sensitivities of credit spreads to option values.[2]

Second, we test the empirical validity of the theoretical hedge ratios by collecting data on both American put options on stocks and CDS spreads on corporate bonds for a sample of 106 companies from August 2001 to June 2014. We test whether they are in line with those observed empirically and find that the sensitivities of credit spread changes to option returns are in line with the models. However, differently from the case of stocks, we find that hedge ratio regressions improve adjusted R-squared values by 7 percentage points (to 0.20) relative to empirical regressions of credit spread changes on option returns and interest rate changes (with adjusted R-squared values of 0.13). This improvement in the ability of the regression model to explain more of the variability of the credit spread changes is corroborated by an analysis of hedging effectiveness based on model hedge ratios versus empirical hedge ratios. In an out-of-sample analysis, the latter produces a 16% reduction in portfolio volatility relative to an unhedged long credit risk position. The former reduces volatility by an additional 15%.

Our findings are important as they support our new framework to hedge credit risk based on sensitivities from structural models which determine the replicating option portfolio. Our approach is fundamentally different from what has been suggested by practitioners (JPMorgan, 2006), according to which the composition of the replicating option portfolio is determined by the loss at default which is uncertain due to recovery risk. Rather than hedging the default loss, we instead propose hedging changes in the market value of a long credit risk position. Our results suggest that the latter approach would involve a reduction in hedging costs of over 80% for a portfolio of short CDS positions (which includes our sample of firms) on a notional amount of $10 million.

[2] In a recent paper, Geske *et al.* (2016) study the pricing performance of the compound option model and find that, relative to the model of Black and Scholes (1973), pricing errors of individual stock options can be reduced across all strikes and maturity dates and that greater improvements are achieved for long-term options and for firms with higher levels of market leverage. On the other hand, structural models of credit risk are generally unable to accurately replicate corporate bond prices and most of them underestimate credit spreads (Jones *et al.*, 1984; Eom *et al.*, 2004; Huang and Huang, 2012).

Academic studies on the relationship between credit markets and equity options are very limited. Carr and Wu (2010) introduce a methodology that allows joint valuation of CDS and equity options. In another related paper, Carr and Wu (2011) also establish a robust theoretical link between deep out-of-the-money American put options and CDS. In particular, under the assumption that the stock price drops to zero at default, a long position in a put option (scaled by its strike) replicates the payoff of a standardized credit contract. Empirical tests also show that estimates of option-implied and CDS-implied unit recovery claims (or URC) are not statistically different from each other, confirming that the two markets strongly co-move.

A number of empirical studies on the determinants of credit spreads have documented a positive incremental effect of option-implied volatilities and jump risk measures on credit spread levels (Cremers *et al.*, 2008a; Cao *et al.*, 2010) as well as changes (Collin-Dufresne *et al.*, 2001). In particular, Cremers *et al.* (2008a) use panel regressions of credit spreads on both historical and option-implied proxies of return volatility and volatility skew. They find that both implied volatility and (to a lesser extent) implied volatility skew dominate their historical counterparts for long-maturity bonds and lower-rated debt. Similarly, Cao *et al.* (2010) find that option-implied volatilities dominate historical volatility in firm-level time-series regressions of CDS spread levels and that this finding is particularly strong for lower-rated firms. Further investigation of their results reveals that the explanatory power of the implied volatility derives from its greater ability to forecast future volatility and to capture a time-varying volatility risk premium. Collin-Dufresne *et al.* (2001) confirm the importance of option-implied volatility (proxied by changes in the VIX index) and jump risk (proxied by the change in the slope of the "smirk" of implied volatilities of S&P 500 futures options) for explaining credit spread changes. Related to these papers, Cao *et al.* (2011) and Cremers *et al.* (2008b) also show that credit spread levels' pricing errors of structural models of credit risk can be reduced by calibrating them with measures of option-implied volatility and option-implied risk premia, respectively.[3]

Our work is most germane to the study of Schaefer and Strebulaev (2008) who analyze the empirical sensitivities of debt to equity values finding that they are in line with the sensitivities implied by Merton (1974)'s model. Differently from their work, our focus is on hedging credit spreads with equity options by introducing a novel framework to hedge credit risk which blends together the structural credit risk model of Merton (1974) with the compound option pricing model of Geske (1979).

Our work also contributes to the understanding of the unexplored linkages between two liquid derivatives markets, namely the CDS and equity option markets. Other than the theoretical papers by Carr and Wu (2010, 2011), the empirical paper by Berndt and Ostrovnaya (2014) examines CDS spreads and option prices and shows that both markets react faster than the equity market prior to the release of negative credit news.

Past studies have instead investigated the predictive role of options for stock returns (Easley *et al.*, 1998; Cao *et al.*, 2005; Pan and Poteshman, 2006; Bali and Hovakimian, 2009; Cremers and Weinbaum, 2010; Xing *et al.*, 2010; Johnson and So, 2012; An *et al.*, 2014) and that of CDS for stocks returns (Norden and Weber, 2009; Acharya and Johnson, 2007; Ni and Pan, 2011; Hilscher *et al.*, 2015; Han *et al.*, 2017). Other studies have examined the contemporaneous relationship between option trading activity and stock returns (Roll *et al.*, 2009) and between CDS spreads and stock returns (Kapadia and Pu, 2012; Duarte *et al.*, 2007; Friewald *et al.*, 2014).[4]

The remainder of the paper is organized as follows. In Section II, we derive the theoretical hedge ratios of credit spreads to equity put option values under the framework of Merton (1974) and Geske (1979). In Section III we describe the data and how we select the final sample of firms. In Section IV, we report our empirical

[3] Other papers investigating the determinants of credit (or CDS) spreads are by Elton *et al.* (2001), Campbell and Taksler (2003), Das and Hanouna (2009), Ericsson *et al.* (2009) and Zhang *et al.* (2009). These studies also include firm leverage, interest rates, the slope of the term structure of interest rates and the return on the S&P 500 index as additional state variables to explain variations in spreads.

[4] Related to these, a number of studies have analyzed the price discovery of credit spreads implied from the CDS, bond, equity and option markets (Blanco *et al.*, 2005; Zhu, 2006; Forte and Peña, 2009; Avino *et al.*, 2013).

results to test the hedging effectiveness of theoretical hedge ratios both in statistical and economic terms. In Section V, we discuss hedging methods adopted by the industry and hedging with stocks. We also compare the hedging costs of the various hedging alternatives. Section VI concludes. The Appendix describes in detail the steps of the derivation of the theoretical hedge ratios.

II Hedging Credit with Puts using Structural Models

This section describes how we derive theoretical hedge ratios of credit spreads to put options using the structural models of Merton (1974) and Geske (1979). According to these models, the firm value V represents the underlying state variable required to specify the models' main outputs. In particular, the credit spread and the option value are both a function of the variable V, which is assumed to follow a diffusion-type stochastic process. In Merton's model, V determines a firm's default, which occurs whenever its value falls below the face value of debt. In Geske's model, V determines whether the option should be exercised when it expires or it should remain unexercised. As the firm value represents the only driving stochastic factor of these two models, the elasticity of the credit spread (CS) to the value of the option (P) is related to the sensitivity of the spread to V and that of V to P by the following relation:

$$\frac{\partial CS}{\partial P}P = \frac{\partial CS}{\partial V}\frac{\partial V}{\partial P}P \tag{1}$$

where ∂ represents the partial derivative symbol.

We then exploit the dependence of the firm's equity value (E) on V (due to the equity being a European call option on the firm's asset value) and re-write Equation (1) as follows:

$$\frac{\partial CS}{\partial P}P = \frac{\partial CS}{\partial V}\frac{\partial V}{\partial P}P = \frac{\partial CS}{\partial V}\frac{\partial V}{\partial E}\frac{\partial E}{\partial P}P \tag{2}$$

As they define the weights in the hedging portfolio, we refer to these sensitivities as hedge ratios. While these sensitivities can be estimated by a linear regression of credit spread changes on the returns of a put option on the firm's stock, time variation in the elasticity can only be captured by the theoretical hedge ratios based on structural models. In Appendix A, we show the various steps taken to solve the three partial derivatives in Equation (2) which provide the following solution for the theoretical hedge ratios (hr_P):

$$hr_P = \frac{\partial CS}{\partial P}P = -\frac{1}{\tau}\frac{\frac{\phi[h_2(d,\sigma_V^2\tau)]}{V\sigma_V\sqrt{\tau}} + \frac{1}{De^{-r\tau}}(\Phi[h_1(d,\sigma_V^2\tau)] - \frac{\phi[h_1(d,\sigma_V^2\tau)]}{\sigma_V\sqrt{\tau}})}{\Phi[h_2(d,\sigma_V^2\tau)] + \frac{1}{d}\Phi[h_1(d,\sigma_V^2\tau)]} \frac{-\Phi[h_2(d,\sigma_V^2\tau)]}{\Phi[h_1(d,\sigma_V^2\tau)]\Theta[-h_3(\bar{d},\sigma_V^2\tau_1), h_2(d,\sigma_V^2\tau); -\sqrt{\tau_1/\tau}]}P, \quad (3)$$

where

$$d = \frac{De^{-r\tau}}{V},$$

$$\bar{d} = \frac{\bar{V}e^{-r\tau_1}}{V},$$

$$h_1(d,\sigma_V^2\tau) = \frac{-(\sigma_V^2\tau/2 - \ln(d))}{\sigma_V\sqrt{\tau}},$$

$$h_2(d,\sigma_V^2\tau) = \frac{-(\sigma_V^2\tau/2 + \ln(d))}{\sigma_V\sqrt{\tau}},$$

$$h_3(\bar{d},\sigma_V^2\tau_1) = \frac{-(\sigma_V^2\tau_1/2 + \ln(\bar{d}))}{\sigma_V\sqrt{\tau_1}},$$

V = current value of the firm's assets,

$\bar{V}$ = value of V such that

$$V\Phi[h_2(d,\sigma_V^2\tau) + \sigma_V\sqrt{\tau-\tau_1}] - De^{-r(\tau-\tau_1)}\Phi[h_2(d,\sigma_V^2\tau)] - K = 0,$$

D = face value of the debt,

r = the risk-free rate of interest,

τ = maturity date of the debt,

τ_1 = maturity date of the put option,

σ_V^2 = the instantaneous variance of the return on the assets of the firm,

K = strike price of the put option,

$\phi[\cdot]$ = univariate normal density function,

$\Phi[\cdot]$ = univariate cumulative normal distribution function,

$\Theta[\cdot]$ = bivariate cumulative normal distribution function.

As $\frac{\partial CS}{\partial V} < 0$, $\frac{\partial V}{\partial E} > 0$ and $\frac{\partial E}{\partial P} < 0$, hedge ratios implied by the theory predict a positive relationship between changes in option values and credit spread changes ($\frac{\partial CS}{\partial P} > 0$).

III Sample Selection and Data Construction

We obtain our data on U.S. dollar-denominated CDS spreads from Bloomberg. Our sample consists of monthly observations from August 2001 to June 2014 for a total of 155 time-series observations. The information about CDS spreads is extracted using five-year maturity contracts (as they are the most actively traded) on senior unsecured debt.

We start with an initial sample of 1,213 corporate reference entities with CDS contracts traded. From these, we were able to identify 965 North American firms having equity market data (stock prices and outstanding number of shares adjusted for stock dividends and splits) in the Center for Research on Security Prices (CRSP) database based on their Committee on Uniform Security Identification Procedures (CUSIP) number. We focus only on corporates with daily CDS data available for a minimum of seven consecutive years during our sample period. After applying this filter we are left with 207 reference entities. For some of these firms we were not able to find accounting data on company debt from Compustat, leaving us with 189 firms.

Using the CUSIP identifier, we match CDS data with option data from OptionMetrics using the Security file, the Security Price file, the Distribution file and the Option Price file all available in the database. As we want to focus on highly liquid contracts, we select put options with a short maturity of one month, on average (Bondarenko, 2014). This also allows us to create a monthly time series of option returns matched with the monthly time series of CDS spread changes. In particular, the options are purchased the first day after the expiration of the previous month's option which is usually on the next Monday following the third Friday of each month. We get information about the following characteristics of the put options: strike price, maturity, moneyness, open interest and implied volatility.

We apply the following filters to the option data: the bid price is positive and strictly smaller than the ask price, the traded volume and the open interest are both positive. To construct our time series of options we need to choose only one put option contract among all those traded on the day when we purchase the option. Given the established link between CDS contracts and out-of-the-money (OTM) put options (Carr and Wu, 2011), we build a monthly time series of put options which are, on average, OTM. We start by selecting put options with moneyness (defined as the ratio of strike to stock price) lower than 0.90. In the eventuality that no option is traded on a given day with such moneyness levels, we replace it with an option with moneyness lower than 0.925. If there is still no option available, we select one with moneyness lower than 0.95. If there are no options available with this moneyness level, we select one with moneyness lower than 0.975. If still we cannot find options, we select one put option with moneyness lower than 1. This algorithm allows us to create a continuous monthly time series of option returns based on a sample of put options which are, on average, OTM.

Hence, each month, we select one put option with the highest open interest that meets all the above characteristics. After applying the previous option filters, we lose an additional 83 firms, leaving us with a final sample of 106 firms.

From Table 1 we can observe that most firms in our final sample are rated BBB (43 firms) and A (39 firms). The remaining firms are AAA-rated (only 1 firm), AA-rated (12 firms) and BB-rated (11 firms). Credit ratings are from Compustat and are based on the Standard & Poor's credit rating agency. In order to assign credit ratings to each firm, we download ratings each year during the sample period, transform them into numerical values, take an average over the years and convert the number into a rating again.[5]

Table 1 also reports summary statistics on our sample of put options. The mean maturity and moneyness of the put contracts are 28 calendar days and 0.93, respectively. The mean delta and open interest are -0.25 and 4,330, respectively. The open interest varies considerably across rating categories: it is higher for the best-rated firms (and equal to 7,709) and lower for BBB-rated firms (equal to 2,786).

We compute put option returns in two different ways: using dollar returns and arithmetic returns. Dollar returns are obtained from the difference between the option payoff at maturity and the option price on the trading date. Arithmetic returns are obtained by dividing the dollar returns by the option price.[6]

Table 2 describes the main summary statistics for both CDS spread changes and option returns. Panel A of the table shows that the average CDS spread change is negative and ranges from about -0.10 basis points for the AAA-AA and A-rated companies to -1.16 basis points for BB-rated companies. The standard deviation of CDS spread changes is 32 basis points for the whole sample of firms and increases as the credit rating deteriorates. The probability distribution of CDS spread changes is non-normal as shown by the positive values of skewness and high levels of kurtosis. Panel B of the table shows that average put option dollar returns are negative (of 1 cent) and range from a negative value of 16 cents for the highest-rated firms to a positive value of 8 cents for BB-rated firms. The standard deviation of option dollar returns is of \$2.07 for the whole portfolio of firms. Similar to CDS spread changes,

[5]The main empirical findings of this paper are based on the use of average ratings. However, as a robustness, we repeat the empirical analysis using the rating available at the end of the sample period for each firm and obtain very similar results. These results are available on request from the authors.

[6]In unreported results, we also computed midpoint percentage returns: they are defined as the ratio of dollar returns and the average value of the option price on the trading date and the option payoff at maturity. We compute these because, differently from stock returns, arithmetic returns for options are quite large. This is particularly true for OTM options that, more often than others, would expire unexercised with a negative return of 100%. Given that we define theoretical hedge ratios in terms of derivatives, we expect to find that these hedge ratios would be more accurate at capturing smaller price changes as implied from midpoint percentage returns. We investigate this point further in Section IV.*A*.

option dollar returns are also positively skewed with positive kurtosis with higher values for these statistics confirming that option returns are highly non-normal. Finally, Panel C of the table reports summary statistics for put option simple returns: mean returns are positive and equal to 9% for the whole sample of firms but are negative of 38% for the highest-rated firms and higher than 10% for the firms in the remaining rating categories. The standard deviation of these returns is very high and equal to 452% for the entire sample. Positive skewness values and high kurtosis levels confirm that option returns are highly non-normal.

IV Empirical Analysis

This section includes the main empirical results of this paper. We compare the empirical sensitivities of credit spreads to put option values with the sensitivities implied by the structural models of Merton (1974) and Geske (1979). The hedging effectiveness of both empirical as well as model hedge ratios are assessed. Finally, we examine the impact of the other determinants of credit spread changes on the empirical sensitivities.

A. Contingent Claims Approach and Sensitivities of Debt to Equity Options

A.1 Empirical Sensitivities of Credit Spreads to Put Options

We start by estimating the sensitivity of CDS spreads to changes in the value of the firm by regressing, for each firm j, CDS spread changes ($\Delta CDS_{j,t}$) on the returns on options on stocks issued by the firm ($ret_{option_{j,t}}$). Similar to Schaefer and Strebulaev (2008), our regressions also control for changes in the riskless interest rate by including the change in the 10-year constant maturity Treasury bond rate (Δr_t^{10}). In particular, we estimate the following time-series regression model for each firm in our sample:

$$\Delta CDS_{j,t} = \alpha_j + \beta_{j,O} ret_{option_{j,t}} + \beta_{j,r} \Delta r_t^{10} + \epsilon_{j,t} \quad (4)$$

Table 3 reports average estimated coefficients and their t-statistics, which are computed in the same way as in Collin-Dufresne *et al.* (2001) and Ericsson *et al.* (2009). These t-statistics account for the cross-sectional variation in the time-series regression coefficient estimates. Estimated coefficients and t-statistics are shown for option dollar returns (Panel A), arithmetic option returns (Panel B) and midpoint percentage returns (Panel C). The estimated coefficients on option returns and the change in the riskless rate are highly significant for the whole sample, for all rating categories and under each definition of option returns. Interestingly, the estimated coefficients for both explanatory variables are of comparable magnitude in the three panels and become larger for lower credit rating categories. These results are economically significant: focusing on Panel A and the whole sample of firms, a 1% increase in the riskless rate reduces CDS spreads by 16 basis points, whereas a 1 U.S. dollar increase in option returns increases CDS spreads by about 7 basis points.[7] The two factors explain approximately 13% of the variation in the spreads for the whole sample, but adjusted R^2 are higher for the lowest-rated firms. The negative correlation between CDS spreads and the risk-free rate is in line with the findings by Ericsson *et al.* (2009) and Longstaff and Schwartz (1995). In Figure 1, we plot the time-series correlations between changes in CDS spreads and option returns. We can observe a positive relationship which confirms the statistical link between these two variables documented in Table 3.

A.2 Analysing Theoretical Hedge Ratios

In order to study the ability of structural models to provide good predictions of hedge ratios, we estimate the following regression model:

$$\Delta CDS_{j,t} = \alpha_j + \alpha_{j,O} hr_{P_{j,t}} ret_{option_{j,t}} + \beta_{j,r} \Delta r_t^{10} + \epsilon_{j,t} \quad (5)$$

[7]Similarly, in Panel B, a 1% increase in the riskless rate reduces CDS spreads by 14 basis points, whereas a 100% increase in option returns increases CDS spreads by about 4 basis points.

where $hr_{P_{jt}}$ is the theoretical hedge ratio for firm j at time t that we defined in Equation (3). If the combined models of Merton (1974) and Geske (1979) were accurate, $\alpha_{j,O}$ would not be statistically different from one. Before estimating the regression model in Equation (5), a number of parameters have to be estimated for each firm including: the market leverage (D/V), the asset volatility (σ_V), the time-to-maturity of the debt (λ), the time-to-maturity of the put option (λ_1), the strike price of the option (K) and the risk-free rate of interest (r).

We estimate D/V by taking the ratio of the book value of debt (the sum of Compustat quarterly items for long-term debt and debt in current liabilities)[8] to the market value of assets (the product between the number of shares outstanding and the stock price taken from CRSP plus the book value of debt). The Compustat data refer to the most recent quarterly accounting report, whereas the CRSP data are obtained on the observation date. As our main objective is to assess the ability of both Merton (1974)'s and Geske (1979)'s models to generate accurate sensitivities of credit spreads to put option values, we need to take special care to avoid that our results are somehow contaminated by the fact that we use these same models to estimate the main inputs required to determine the theoretical hedge ratios. For example, because these sensitivities also depend on the estimated asset volatility, we are careful not to use any of these models for the purpose of generating the asset volatility input. Instead, similar to Schaefer and Strebulaev (2008), we adopt a model-free approach. In particular, we use the approach proposed by Bharath and Shumway (2008) that does not require any sort of estimation or optimization but has been shown to generate probabilities of default that perform slightly better in out-of-sample forecasts than the Merton distance-to-default model. In light of this, we compute a firm's asset volatility as follows:

$$\sigma_{V_{j,t}} = \frac{E_{j,t}}{E_{j,t}+D_{j,t}}\sigma_{E_{j,t}} + \frac{D_{j,t}}{E_{j,t}+D_{j,t}}\sigma_{D_{j,t}} = \frac{E_{j,t}}{E_{j,t}+D_{j,t}}\sigma_{E_{j,t}} + \frac{D_{j,t}}{E_{j,t}+D_{j,t}}(0.05+0.25*\sigma_{E_{j,t}}) \tag{6}$$

where $\sigma_{E_{j,t}}$ and $\sigma_{D_{j,t}}$ represent the time t volatility of firm j's equity and debt

[8] We use items 45 and 51 for debt in current liabilities and long-term debt, respectively.

returns, respectively. $E_{j,t}$ and $D_{j,t}$ are the equity value (computed as the number of shares outstanding multiplied by the closing stock price) and the debt book value of firm j at time t, respectively. In our main analysis, we use the option-implied volatility (provided by OptionMetrics) as a proxy for the equity volatility. However, we also compute model hedge ratios based on a historical volatility measure which estimates the time t volatility as the time-series volatility of returns on firm's j equity using three years of monthly observations up to month t.

We use 5-year as the time-to-maturity of the debt as this is the most liquid segment of the term structure of CDS spreads and the most widely used in previous empirical studies on CDS. The time-to-maturity of the option is fixed at 1-month as these short-term contracts are highly liquid (Bondarenko, 2014). The strike price of the option is that of the put contract selected each month and is needed to estimate $\bar{V}$ which is a required input in Equation (3). We assume a constant risk-free rate of interest of 3.6% as this is its average value during our sample period.

Table 4 reports estimates of leverage ratios and volatilities. Equity volatilities are based on historical moving averages (Panel D) or implied from put options (Panel B) and increase for lower-rated firms. Implied volatilities are a few percentage points higher than historical volatilities. The same pattern can be observed for the asset volatility estimates based on both historical equity volatility (Panel E) and equity-implied volatility (Panel C). The market leverage in Panel A shows a non-monotonic pattern: it is higher for the best- and worst-rated firms and takes on intermediate values for BBB-rated firms.[9] While the volatility patterns are generally in line with previous studies (Schaefer and Strebulaev, 2008), our leverage patterns are somewhat different due to the inclusion of financial firms in our sample that belong to the AAA-AA and A rating categories.[10]

Table 5 shows summary statistics for estimated hedge ratios based on Equation

[9] It is worth noting that when we estimate the historical volatility, the number of observations is lower due to missing equity prices in the early part of our sample for six firms. As these missing values do not allow us to construct a complete time series of historical volatility, we decide to exclude these firms from the sample. The same firms are instead included in the final sample when option-implied volatilities are used. In fact, the latter are available from the start of our sample.

[10] Excluding these financial firms from our sample results in leverage ratios increasing as the credit rating deteriorates, which is in line with past studies.

3 using both historical equity volatility ($hr_P(\sigma^A_{HIST})$) and option-implied volatility ($hr_P(\sigma^A_{IMP})$) as inputs for the estimation of a firm's asset volatility (computed as from Equation (6)). Hedge ratios increase monotonically as the credit rating declines from about 1-2 basis points for AAA-AA category to 7-8 basis points for the BB category. Hedge ratios based on option-implied volatilities are higher than hedge ratios based on historical volatilities across all rating categories. In our subsequent analysis, we use option-implied volatilities as they allow us to work with a larger sample of firms and have been shown to dominate their historical counterparts in explaining bond yield spreads and CDS spreads (Cremers *et al.*, 2008a; Cao *et al.*, 2010). A time-series plot of these hedge ratios is shown in Figure 2a for a portfolio including the whole sample of firms. From the plot, it can be observed that hedge ratios increase during periods of market turbulence such as in the dotcom bubble and the financial crisis of 2007-2009, when they reached values of about 15 and 30 basis points, respectively.

A.3 Testing Structural Models Predictions of Hedge Ratios

Next we directly test whether the theoretical hedge ratios are consistent with the empirical sensitivities of CDS spreads to equity puts. To this end, we estimate the regression model in Equation (5) for each firm j using the hedge ratio based on our estimate of asset volatility, $hr_P = hr_P(\sigma^A_{IMP})$. If the structural models of Merton (1974) and Geske (1979) produce accurate predictions of these sensitivities, then the estimated coefficient $\alpha_{j,O}$ should not be statistically different from one.

We follow Schaefer and Strebulaev (2008) and use average hedge ratios for each rating class as an estimate of $hr_{P_{j,t}}$ in order to mitigate the noise which may affect the firm-specific estimates of asset volatility. In particular, we start by estimating the theoretical hedge ratios for each firm j from the asset volatility estimate. We then compute the average hedge ratio for each month during our sample period and for each rating category.[11] This average hedge ratio is used for the regression model

[11]Subrating categories are ignored in our analysis. This means that, for example, AA- or AA+ would both be classed as AA. We treat the remaining subratings in a similar manner.

in Equation (5).

Table 6 provides the results of the hedge ratio regressions for option dollar returns (Panel A), arithmetic returns (Panel B) and midpoint percentage returns (Panel C). In the case of the whole sample, the mean estimate of $\alpha_{j,O}$ is not statistically different from one for dollar returns (0.96 with t-statistic against unity of -0.37) and midpoint percentage returns (1.02 with t-statistic against unity of 0.11) whereas it is significantly lower than one for arithmetic returns (and equal to 0.77 and t-statistic against unity of -2.29). A more careful examination of the results reveals that the combined structural models of Merton (1974) and Geske (1979) provide accurate predictions of put option sensitivity of CDS spreads for all rating categories except the AAA-AA for which the null that $\alpha_{j,O} = 1$ is rejected at the 5% and 10% levels for simple returns and midpoint percentage returns, respectively. Excluding the AAA-AA category, the mean estimate of $\alpha_{j,O}$ varies between 0.76 (for A-rated firms and arithmetic returns) and 1.52 (for BB-rated firms and midpoint percentage returns). The estimates of the coefficient are generally increasing as the rating declines. An interesting observation to make relates to the adjusted R^2 of the regressions. In particular, for the whole sample, they can be up to 8 percentage points higher than the adjusted R^2 shown in Table 3 for the empirical sensitivity regressions. For BBB-rated firms and the case of percentage returns, adjusted R^2 are 13 percentage points higher than what reported in Panel B of Table 3. This increase in the explanatory power of the regressions is interesting as it is specific of option sensitivities and cannot be observed when predicting the equity sensitivity using Merton (1974)'s model as shown in Section V.A. and as already documented for bond returns by Schaefer and Strebulaev (2008).

B. Hedging Effectiveness

The significant increase in explanatory power for CDS spread changes attributable to the model hedge ratios (documented in Table 6) prompts us to investigate further whether the hedging effectiveness of a short position in a portfolio of CDS contracts improves when the replicating option portfolio is constructed using the theoretical hedge ratios rather than empirical sensitivities. Furthermore, we are also interested to examine whether hedging a long credit risk position with put options is effective compared to the unhedged case.

In order to perform this analysis, we assume that the main aim of a CDS dealer is to minimize the monthly volatility of a hedged short CDS portfolio position including N reference entities. Each of the N contracts is for a notional amount of \$10 million and is hedged with $\delta_{j,t}$ put option contracts. We compute the mean portfolio hedging error (e_t) on each month t as follows:

$$e_t = \frac{1}{N}\sum_{j=1}^{N}[-(CV(CDS_{j,t+1}) - CV(CDS_{j,t})) + \delta_{j,t} ret_{option_{j,t+1}}], \quad (7)$$

where $\delta_{j,t}$ represents the number of put option contracts on firm j's stock which are required to hedge a short position in one CDS contract at time t.[12] $CV(CDS_{j,t})$ is the mark-to-market value of the CDS contract. $ret_{option_{j,t+1}}$ is the dollar return on the option contract.

The two main challenges we now face relate to the computation of both $CV(CDS_{j,t})$ and $\delta_{j,t}$. The former requires the use of a CDS pricing model. The latter is complicated by the fact that our theoretical hedge ratios (as well as the empirical hedge ratios) are expressed in basis points. Hence, they cannot directly tell us the number of options required for hedging a short CDS position.

We address the first challenge by using the ISDA CDS standard model that can be implemented on Bloomberg's 'CDSW' function. We use this model to compute the CDS duration (D) which we define as the average change in the mark-to-market value for a plus/minus 1 basis point change in the CDS spread:[13]

$$D_{j,t} = \frac{1}{2}[|CV(CDS_{j,t}+1) - CV(CDS_{j,t})| + |CV(CDS_{j,t}) - CV(CDS_{j,t}-1)|]. \quad (8)$$

According to this pricing model, a change in the value of the CDS contract will

[12]Clearly, in case of no hedging, we have that $\delta_{j,t} = 0$.

[13]More detailed information on the ISDA pricing model (including documentation and source code) can be found at www.cdsmodel.com. The same model has been previously used in a similar way by Che and Kapadia (2012) to study Merton (1974)'s hedge ratios of CDS spreads to equity.

depend on the current level of the spread. For each CDS portfolio and each month, we then compute the mark-to-market value of the CDS portfolio by multiplying the average CDS spread by the average duration of the portfolio.

We use the duration of a CDS contract also to deal with our second challenge. In particular, we compute the total dollar amount to be invested in put options by multiplying the model (or empirical) hedge ratio (expressed in basis points) by the CDS duration computed as in Equation (8). We can then obtain the total number of put options to buy ($\delta_{j,t}$) by simply dividing this total dollar amount by the put option price.[14]

We finally examine the magnitude of hedging errors by computing the root mean square error (RMSE) as follows:

$$RMSE = \sqrt{\frac{1}{T}\sum_{t=1}^{T} e_t^2}, \tag{9}$$

where T is the number of months for which hedging errors can be computed.

Table 7 reports the RMSE of the monthly hedging errors for the unhedged case, hedging using theoretical hedge ratios and hedging using empirical sensitivities. Panel A is based on the whole sample period, whereas Panel B produces out-of-sample empirical hedge ratios using time-varying estimated coefficients $\beta_{j,O}$ from the regression model in Equation (4). Time variation in coefficient estimates is obtained by estimating the regression model each month using a rolling window of 4 years of monthly data. For comparison, Panel B also shows the RMSE under the unhedged case as well as the hedging scenario based on theoretical hedge ratios.

The first interesting thing to notice is that hedging credit risk with put options allows to reduce the RMSE of the portfolio by 29% and 25% using theoretical hedge ratios and empirical hedge ratios, respectively. However, to have a more detailed idea of the hedging performance, we can compare the RMSE values across rating categories. Focusing on model hedging, we observe lower RMSE values for all rating

[14] The average duration for our sample of firms is 4,710. The average durations for each rating categories are 4,956, 4766, 4,603 and 4,487 for AAA-AA, A, BBB, and BB, respectively.

categories even though the most significant decreases involve A-rated and BBB-rated firms. Empirical hedge ratios generate less sizable reductions in RMSE for these two rating categories, they slightly outperform model hedge ratios for the AAA-AA rating but they underperform the unhedged case for the lowest rating category.

Panel B is based on an out-of-sample analysis and supports the in-sample results: the hedging effectiveness based on model hedge ratios is generally superior to that achieved using empirical sensitivities. For the entire sample, the average RMSE is reduced from $78,103 to $65,314 if empirical sensitivities are used. However, the RMSE can be decreased at $56,683 (a further 15% reduction) if model hedge ratios were instead implemented and the most significant decreases in the RMSE are obtained for the A, BBB and BB ratings.

C. Other Determinants of Credit Spreads

We evaluate the effect of additional control variables that previous studies have used to explain credit spread changes (Collin-Dufresne *et al.*, 2001; Ericsson *et al.*, 2009). In particular, we consider the changes in the slope of the yield curve (which is defined as the difference between the 10-year and the 2-year Treasury rates), the return on the S&P 500 index and the changes in the *VIX* index of implied volatility of options on the S&P 100 index. The monthly time series of interest rates as well as the S&P 500 returns are downloaded from Datastream. The time series of the *VIX* index is obtained from the Chicago Board Options Exchange.

Table 8 shows the results of the multivariate regression model. We find that the estimated coefficient on the change in the 10-year interest rate is, on average, about 10 basis points higher than the estimated value in Table 3 for all firms in our sample. We also observe that the coefficients on option dollar returns are a bit lower by about 4 basis points but still highly significant (except for the rating category *AAA-AA*). The estimated coefficients on the remaining control variables are in line with those reported by Ericsson *et al.* (2009) and Collin-Dufresne *et al.* (2001) for their regressions of CDS (and credit) spread changes, respectively: for example, the coefficient on the equity volatility that we get for all firms in our sample is

0.72 which is in the range of values that they report even though they estimate volatility differently. Our estimated effect of a 1% increase in the S&P 500 return on CDS spread changes is negative and of about 1.61 basis points which is in line with estimates obtained by Collin-Dufresne *et al.* (2001). Similarly, we also observe an insignificant effect of the slope of the yield curve. The adjusted R-squared values of our regression models range from 0.26 (for the *AAA-AA* rating category) to 0.34 (for the lowest-rated firms) and are extremely similar to the range of values Ericsson *et al.* (2009) report (between 0.30 and 0.32).

In unreported results, we find that our theoretical hedge ratios are highly correlated with both *VIX* changes and S&P 500 returns. Simply regressing the model hedge ratios on *VIX* changes, S&P 500 returns and changes in the slope of the yield curve generates an adjusted R-squared value of almost 70%. The fact that these control variables are highly significant implies that our model hedge ratios are able to efficiently incorporate most information contained in these additional variables which are not directly related to credit exposure and to the fundamentals underlying structural models of credit risk.

V Further Analysis

This section discusses hedging credit risk using stocks as well as an industry application of hedging CDS using put options. Finally, the hedging costs using both stocks and put options are estimated.

A. Hedging Credit with Stocks

Past papers have investigated the ability of Merton (1974)'s model to generate accurate sensitivities of bond returns to equity ((Schaefer and Strebulaev, 2008)) or CDS spread changes to equity ((Che and Kapadia, 2012)). We carry out a similar analysis using our sample of CDS firms. We start by defining the model hedge ratios exploiting the dependence of debt to the firm value V, which is the only stochastic variable in Merton (1974):

$$\frac{\partial CS}{\partial E}E = \frac{\partial CS}{\partial V}\frac{\partial V}{\partial E}E = -\frac{1}{\tau}\frac{\frac{\phi[h_2(d,\sigma_V^2\tau)]}{V\sigma_V\sqrt{\tau}} + \frac{1}{De^{-r\tau}}(\Phi[h_1(d,\sigma_V^2\tau)] - \frac{\phi[h_1(d,\sigma_V^2\tau)]}{\sigma_V\sqrt{\tau}})}{\Phi[h_2(d,\sigma_V^2\tau)] + \frac{1}{d}\Phi[h_1(d,\sigma_V^2\tau)]}\frac{E}{\Phi[h_1(d,\sigma_V^2\tau)]} \quad (10)$$

where all variables are as previously defined and details on the derivation of these two partial derivatives can be found in Appendix A. The parameters required to estimate these hedge ratios are the same as those discussed in Section IV.*A.2*.

Empirical sensitivities of CDS spreads to stock returns are computed using the same approach adopted in Section IV. Panel A of Table 9 reports average coefficient estimates (and their t-statistics) from time-series regressions of CDS spread changes on a constant, stock returns and changes in the riskless interest rate. We find that the coefficients on both stock returns and the riskless rate are highly significant for the whole sample and for each rating category. In particular, for the whole sample, a 1% increase in stock returns decreases CDS spreads by 1.44 basis points. The magnitude of this negative relationship increases as the company rating deteriorates. Similarly, a 1% increase in the risk-free rate produces a reduction in CDS spreads of about 11 basis points and the impact of this effect is greater for lower-rated firms.

We use Equation (10) to compute the sensitivity of CDS spread changes to changes in the value of a firm's equity. We then test the accuracy of these sensitivities based on Merton (1974) by running the following regression model:

$$\Delta CDS_{j,t} = \alpha_j + \alpha_{j,S} hr_{S_{s,t}} ret_{stock_{j,t}} + \beta_{j,r}\Delta r_t^{10} + \epsilon_{j,t} \quad (11)$$

where $ret_{stock_{j,t}}$ and $hr_{S_{jt}}$ are the stock log-return (in percentage) and the mean theoretical hedge ratio for all firms in rating s at time t, respectively.

If Merton (1974)'s model hedge ratios are accurate, we would expect to estimate a value of $\alpha_{j,S}$ not statistically different from one.

Panel B of Table 9 shows that the estimated coefficient $\alpha_{j,S}$ is not statistically different from one for the whole sample as well as for each rating group. The alignment between the empirical sensitivities and those based on Merton (1974) is also confirmed by similar adjusted R^2 values obtained from the regression models in both Panel A and B of the table.

Panel A of Table 10 presents the main results on the hedging effectiveness of stocks using the whole sample period. In particular, in Equation (7) we replace $ret_{option_{j,t+1}}$ with $ret_{stock_{j,t+1}}$ (the net stock return on firm j over period t+1) and $\delta_{j,t}$ would instead represent the dollar amount of equity of firm j required to hedge a short position in one CDS contract at time t.[15] Our analysis shows that hedging credit risk using stocks allows a reduction in monthly portfolio volatility of about 20% for the entire sample of firms. Further, empirical hedge ratios are generally more effective for BBB-rated and BB-rated portfolios of firms.

Our findings confirm for our sample of firms that Merton (1974)'s model is able to generate accurate predictions of the debt-to-equity sensitivity in line with previous studies (Schaefer and Strebulaev, 2008; Che and Kapadia, 2012).

B. Industry Application to Computing Hedge Ratios

JPMorgan (2006) introduced credit risk hedging methods based on trading CDS contracts and equity put options. In particular, the number of put contracts to be purchased to hedge a long credit risk position (short CDS position) can be computed as follows:

$$Puts = \frac{N \times (1 - R)}{100 \times (K - E_D)} \tag{12}$$

where N is the notional principal of the CDS contract, R is the recovery rate on the corporate bond (underlying the CDS contract) issued by the reference entity, K is the strike price of the put option and E_D represents the stock price of the reference entity in the occurrence of a credit event. We follow JPMorgan (2006) and set R and E_D equal to 0.5 and \$0.5, respectively. We set N equal to \$10 million.

This approach assumes a default-neutral portfolio structure because the number of put contracts to buy is defined as to achieve a gain in default which is the same as the default loss on the short position of the CDS contract. In other words, the

[15] The value of $\delta_{j,t}$ is computed either from empirically observed sensitivities or from Merton (1974)'s model using Equation (10).

default loss to be paid by the protection seller is set to be the same as the default gain on the puts.

We investigate the effectiveness of this approach to hedge changes in the market value of the CDS contract from the perspective of a CDS seller. In Equation (7) we set $\delta_{j,t}$ equal to the number of put contracts to buy on firm j's stock at time t computed according to Equation (12).

Based on the whole sample period, Panel B of Table 10 shows sizeable increases in RMSE values of over 50%. This result is not surprising if we consider that the main aim of this industry method is to neutralize the default loss amount, not losses in the mark-to-market value of a short position in a CDS contract. From this point of view, the hedging approach we introduce in this paper can be regarded as a valid alternative to existing methods currently adopted by practitioners.

C. The Costs of Hedging

We determine the hedging costs of three alternative hedging strategies which include trading stocks based on Merton (1974)'s model hedge ratios, stock options based on our theoretical hedge ratios combining Merton (1974) and Geske (1979), and stock options based on JPMorgan (2006).

Table 11 shows the dollar amount required to hedge a short CDS portfolio. For the theoretical hedge ratios, this is computed by multiplying the mean model hedge ratio (in basis points) by the mean CDS duration of the portfolio. For the practitioner approach, we follow JPMorgan (2006) and multiply the output of Equation (12) by the product of 100 and the put price (averaged across reference entities included in the portfolio). We also report the number of shares or put options required by each hedging strategy. This is obtained by dividing the dollar amount by the stock price or the option price (averaged across reference entities included in the portfolio) in the case of theoretical hedge ratios, whereas it is computed according to Equation (12) for the industry approach.

As can be observed from the table, hedging credit risk using equities represents the most expensive alternative (with an average cost of $260,000 to buy 6,257 shares for a portfolio including all firms in our sample), followed by the hedging method based on equity options suggested by JPMorgan (2006) incurring an average cost of almost \$89,000 to buy 1,710 put contracts. Our theoretical hedge ratios would only incur average hedging costs of almost \$17,000 requiring the purchase of 272 put contracts. Hedging costs increase considerably for portfolios including lower-rated firms.

Figure 2b plots the monthly time series of hedging costs associated with the various hedging strategies. For the entire sample period, hedging with options using our theoretical hedge ratios would have represented the cheapest alternative at each point in time. On the other hand, hedging with stocks would have been the most expensive alternative for the majority of the sample period, except for the tranquil period between mid-2003 and mid-2007. During this period of market stability, hedging with options based on the industry approach incurred the highest costs.

VI Conclusion

We introduce a novel method to hedge credit risk using equity options. Our method determines the sensitivities of credit spreads to put option values by combining the structural credit risk model of Merton (1974) and the compound option pricing model of Geske (1979). We show that these sensitivities are consistent with the empirical sensitivities obtained from regressing credit spread changes on put option returns. Furthermore, the models' hedge ratios induce a greater decrease in portfolio volatility as shown by the out-of-sample RMSE values which are reduced by an additional 15% (relative to RMSE values based on empirical hedge ratios) for a hedged portfolio including all firms in our sample.

Existing methods adopted by practitioners achieve a default-neutral portfolio of CDS and put options whose primary aim is to hedge the loss at default for the protection seller. This default loss is determined ex-ante assuming a given recovery rate and stock price at default of the firm referenced in the CDS contract. Default losses can be large to hedge (the principal notional underlying CDS contracts is of considerable amount) and are subject to recovery risk.

The hedging method presented in this paper represents a valid alternative to industry hedging practices as its main aim is to hedge changes in the market value of a short position in a portfolio of CDS contracts, rather than default losses. This results in substantial reductions in hedging costs.

Future research should investigate the performance of the theoretical hedge ratios introduced in this paper for hedging portfolios of corporate bonds.

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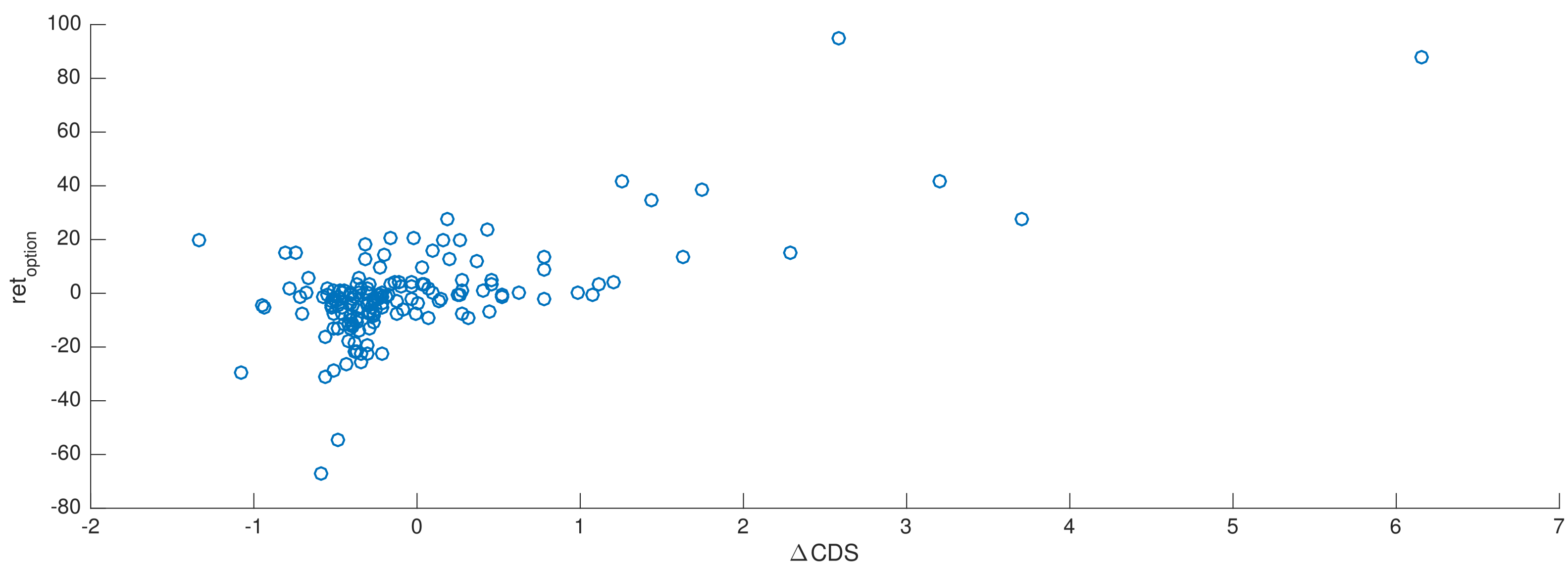
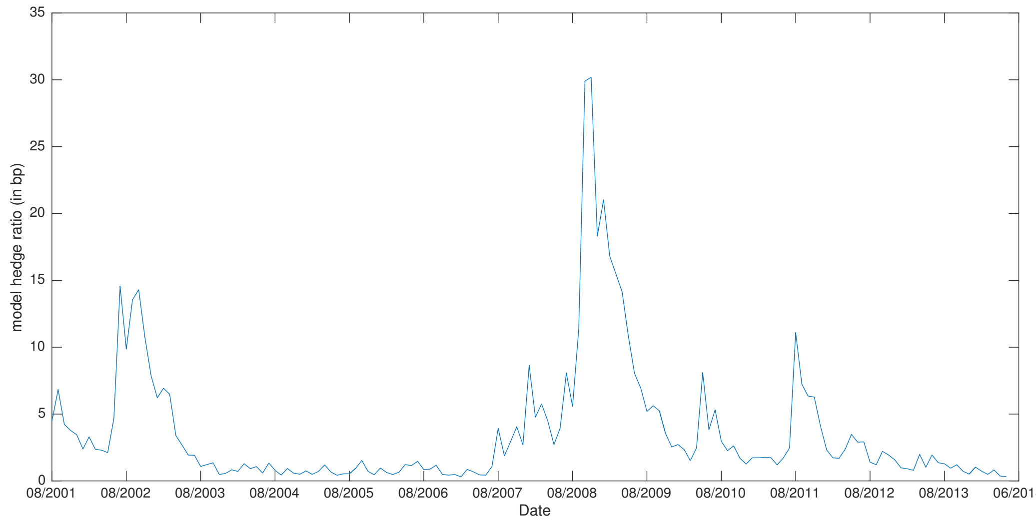
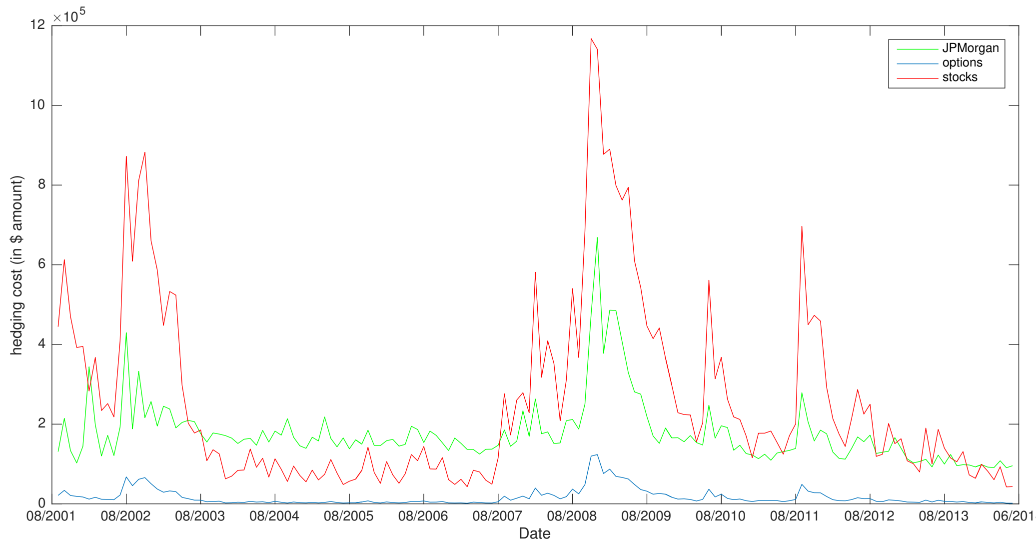


Figure 1: **Time-series relation between CDS spread changes and option dollar returns**

This figure displays the cross-sectional average of the CDS spread changes against the cross-sectional average of option dollar returns for each month from September 2001 to June 2014.



(a) Hedge ratios of credit spreads to put options



(b) Hedging costs

Figure 2: **Time series of hedge ratios and hedging costs**

This figure plots average model hedge ratios (in basis points) and the costs (in U.S. dollars) of hedging a short position in a portfolio of CDS contracts. The top panel shows the time series of average theoretical hedge ratios of credit spreads to put options computed using Equation (3) for the whole sample of 106 firms. The bottom panel displays the time series of hedging costs based on equity hedging, option hedging based on the JPMorgan (2006)'s approach and option hedging using our theoretical hedge ratios. The sample period is from August 2001 to June 2014.

Table 1: **Summary statistics for the final sample of put options**

This table reports summary statistics for the final sample of put options obtained from OptionMetrics during the period August 2001-June 2014. In particular, mean and median values are reported for option maturity (on the trading date), moneyness (defined as the ratio of strike to stock price), open interest and delta. The statistics are first computed for each firm using the time series of each variable and then averaged across firms. Each firm is assigned a credit rating based on its average rating across years for which both CDS and option data are available.

	All	AAA-AA	A	BBB	BB
No. firms	106	13	39	43	11
Mean maturity	28.41	28.39	28.33	28.45	28.50
Median maturity	26.04	26.00	26.00	26.09	26.00
Mean moneyness	0.93	0.94	0.93	0.93	0.92
Median moneyness	0.93	0.94	0.93	0.93	0.93
Mean open interest	4,330	7,709	5,065	2,786	3,763
Median open interest	2,433	4,748	2,908	1,458	1,823
Mean delta	-0.25	-0.25	-0.23	-0.26	-0.29
Median delta	-0.21	-0.21	-0.19	-0.22	-0.26

Table 2: **Summary statistics on monthly CDS changes and option returns**

This table reports summary statistics on the monthly time series of CDS spread changes (expressed in basis points), put option dollar returns (expressed in U.S. dollar) and put option arithmetic returns (expressed in decimals) for the final sample of firms over the period August 2001-June 2014. The statistics are first computed for each firm using the time series of each variable and then averaged across firms. Each firm is assigned a credit rating based on its average rating across years for which both CDS and option data are available. Nobs is the number of observations.

	All	AAA-AA	A	BBB	BB
Panel A: CDS spread changes (in basis points)					
Mean	-0.25	-0.12	-0.09	-0.20	-1.16
Standard Deviation	32.08	13.43	27.41	35.46	57.47
Skewness	1.19	1.19	1.19	1.24	1.01
Kurtosis	15.55	18.89	15.11	15.64	12.85
5% Quantile	-40.45	-16.44	-33.17	-44.25	-79.81
95% Quantile	41.89	17.05	33.13	46.01	86.18
Panel B: Option dollar returns (in U.S. dollars)					
Mean	-0.01	-0.16	-0.03	0.03	0.08
Standard Deviation	2.07	1.50	1.93	2.39	1.97
Skewness	5.45	4.77	5.72	5.56	4.88
Kurtosis	44.61	40.41	47.32	45.27	37.41
5% Quantile	-1.17	-1.32	-1.15	-1.20	-0.98
95% Quantile	2.05	1.68	2.04	2.03	2.57
Panel C: Option arithmetic returns (in decimals)					
Mean	0.09	-0.38	0.13	0.19	0.14
Standard Deviation	4.52	2.27	3.94	5.96	3.62
Skewness	5.86	5.80	5.84	6.24	4.51
Kurtosis	47.56	46.05	46.36	53.14	31.74
5% Quantile	-1.00	-1.00	-1.00	-1.00	-1.00
95% Quantile	4.02	2.34	4.83	3.57	4.90
Nobs	13,273	1,710	5,009	5,322	1,232

Table 3: **Regression of CDS changes on put option returns**

This table reports the results of regressing CDS spread changes on put option returns and Treasury rate changes during the period August 2001-June 2014. We estimate the following time-series regression for each firm j:

$$\Delta CDS_{j,t} = \alpha_j + \beta_{j,O} ret_{option_{j,t}} + \beta_{j,r} \Delta r_t^{10} + \epsilon_{j,t}$$

The average regression coefficients from the time-series regressions are reported. The t-statistics are provided in parenthesis and calculated in the same way as in Collin-Dufresne et al. *(2001).* Δr_t^{10} *is the change in the 10-year constant maturity U.S. Treasury bond rate.* $ret_{option_{j,t}}$ *is the return on the put option, which is computed using dollar returns, arithmetic returns and midpoint percentage returns. All coefficients are in basis points. Nobs is the average number of observations for each CDS portfolio.*

	All	AAA-AA	A	BBB	BB
Panel A: Dollar returns					
Intercept	0.04	-0.09	0.23	0.22	-1.58
	(0.21)	(-0.77)	(1.51)	(0.80)	(-1.69)
ret_{option}	7.27	1.63	5.59	7.88	17.49
	(7.16)	(3.18)	(4.57)	(5.18)	(3.17)
Δr^{10}	-15.61	-11.99	-10.83	-16.96	-31.53
	(-7.96)	(-5.68)	(-7.60)	(-5.83)	(-2.35)
Adj R^2	0.13	0.12	0.12	0.15	0.17
Panel B: Arithmetic returns					
Intercept	0.79	0.07	0.71	1.28	0.03
	(2.94)	(0.59)	(2.33)	(2.27)	(0.04)
ret_{option}	4.26	1.08	3.01	5.18	8.82
	(5.90)	(5.54)	(3.89)	(3.58)	(3.58)
Δr^{10}	-14.30	-11.59	-9.87	-15.06	-30.25
	(-7.18)	(-5.98)	(-6.51)	(-4.60)	(-2.43)
Adj R^2	0.13	0.14	0.11	0.13	0.16
Panel C: Midpoint percentage returns					
Intercept	14.13	4.56	11.63	16.06	26.82
	(7.08)	(3.60)	(4.35)	(4.24)	(4.38)
ret_{option}	9.79	3.12	7.28	11.04	19.88
	(7.51)	(3.97)	(4.73)	(4.43)	(5.09)
Δr^{10}	-13.80	-10.82	-9.41	-14.57	-29.88
	(-7.70)	(-5.94)	(-5.45)	(-4.98)	(-2.91)
Adj R^2	0.14	0.14	0.12	0.14	0.20
Nobs	125.22	131.54	128.44	123.77	112.00

Table 4: **Summary statistics on leverage and volatilities**

This table reports the summary statistics on estimates of leverage and volatility for the final sample of firms over the period August 2001-June 2014. Leverage is defined as the ratio between the book value of liabilities and the market value of assets. σ^E_{IMP} is the equity volatility implied from the put option as provided from OptionMetrics. σ^A_{IMP} is the estimated asset volatility computed using σ^E_{IMP} as a proxy for $\sigma_{E_{j,t}}$ in Equation (6). σ^E_{HIST} is the historical equity volatility computed using the sample volatility over a three-year rolling window. σ^A_{HIST} is the estimated asset volatility computed using σ^E_{HIST} as a proxy for $\sigma_{E_{j,t}}$ in Equation (6). The statistics are first computed for each firm using the time series of each variable and then averaged across firms. Each firm is assigned a credit rating based on its average rating across years for which both CDS and option data are available. Nobs is the number of observations.

	All	AAA-AA	A	BBB	BB
Panel A: Leverage					
Mean	0.36	0.48	0.39	0.28	0.38
Standard Deviation	0.08	0.08	0.06	0.08	0.10
5% Quantile	0.25	0.36	0.31	0.18	0.22
95% Quantile	0.49	0.59	0.51	0.44	0.55
Panel B: σ^E_{IMP}					
Mean	0.37	0.30	0.35	0.38	0.48
Standard Deviation	0.17	0.15	0.16	0.17	0.21
5% Quantile	0.20	0.15	0.19	0.21	0.28
95% Quantile	0.73	0.60	0.69	0.74	0.97
Panel C: σ^A_{IMP}					
Mean	0.28	0.20	0.25	0.30	0.35
Standard Deviation	0.10	0.08	0.10	0.11	0.12
5% Quantile	0.17	0.12	0.15	0.18	0.22
95% Quantile	0.49	0.36	0.45	0.53	0.63
Nobs	13,379	1,723	5,048	5,365	1,243
Panel D: σ^E_{HIST}					
Mean	0.33	0.23	0.31	0.34	0.43
Standard Deviation	0.10	0.06	0.09	0.11	0.12
5% Quantile	0.20	0.15	0.19	0.21	0.27
95% Quantile	0.49	0.35	0.45	0.53	0.62
Panel E: σ^A_{HIST}					
Mean	0.25	0.17	0.23	0.28	0.32
Standard Deviation	0.07	0.04	0.06	0.08	0.08
5% Quantile	0.17	0.12	0.15	0.18	0.22
95% Quantile	0.37	0.26	0.34	0.41	0.45
Nobs	12,577	1,299	4,760	5,275	1,243

Table 5: **Hedge Ratios**

This table reports the summary statistics on estimated hedge ratios using the combined models of Merton (1974) and Geske (1979) and computed as in Equation (3). Hedge ratios are estimated assuming two alternative methods to compute asset volatility. In Panel A, we use σ^A_{IMP} as the estimated asset volatility computed using the implied equity volatility (σ^E_{IMP}) as a proxy for $\sigma_{E_{j,t}}$ in Equation (6). In Panel B, we use σ^A_{HIST} as the estimated asset volatility computed using the historical equity volatility (σ^E_{HIST}) as a proxy for $\sigma_{E_{j,t}}$ in Equation (6). Each firm is assigned a credit rating based on its average rating across years for which both CDS and option data are available. Nobs is the number of observations. Hedge ratios are given in basis points.

	All	AAA-AA	A	BBB	BB
Panel A: $hr_P = hr_P(\sigma^A_{IMP})$					
Mean	3.64	1.77	2.66	4.06	8.43
Standard Deviation	7.21	3.13	5.77	8.02	10.00
5% Quantile	0.00	0.00	0.00	0.00	0.01
95% Quantile	17.71	7.06	12.40	20.42	28.84
Nobs	13,379	1,723	5,048	5,365	1,243
Panel B: $hr_P = hr_P(\sigma^A_{HIST})$					
Mean	2.90	0.80	1.94	3.30	7.04
Standard Deviation	6.36	1.71	4.95	7.33	7.68
5% Quantile	0.00	0.00	0.00	0.00	0.01
95% Quantile	14.11	3.91	7.71	16.97	22.65
Nobs	12,577	1,299	4,760	5,275	1,243

Table 6: **Hedge ratio regressions**

This table reports the results of regressing CDS spread changes on put option returns and Treasury rate changes during the period August 2001-June 2014. We estimate the following time-series regression for each firm j:

$$\Delta CDS_{j,t} = \alpha_j + \alpha_{j,O} hr_{P_{s,t}}(\sigma^A_{IMP}) ret_{option_{j,t}} + \beta_{j,r}\Delta r^{10}_t + \epsilon_{j,t}$$

where $hr_{P_{s,t}}$ *is the mean theoretical hedge ratio at time t for all reference entities in rating s and* σ^A_{IMP} *is estimated according to Equation (6). If the combined models of Merton (1974) and Geske (1979) were accurate,* $\alpha_{j,O}$ *would not be statistically different from one. The average regression coefficients from the time-series regressions are reported. The t-statistics are provided in parenthesis and calculated in the same way as in Collin-Dufresne* et al. *(2001).* Δr^{10}_t *is the change in the 10-year constant maturity U.S. Treasury bond rate.* $ret_{option_{j,t}}$ *is the return on the put option, which is computed using dollar returns, arithmetic returns and midpoint percentage returns. The t-statistics for* $\alpha_{j,O}$ *are with respect to the difference from unity. All coefficients are in basis points. Nobs is the average number of observations for each CDS portfolio.*

	All	AAA-AA	A	BBB	BB
Panel A: Dollar returns					
Intercept	-0.66	-0.17	-0.37	-0.67	-2.21
	(-3.57)	(-1.38)	(-1.64)	(-2.76)	(-1.83)
ret_{option}	0.96	0.84	0.84	1.01	1.29
	(-0.37)	(-0.42)	(-0.81)	(0.09)	(0.75)
Δr^{10}	-18.79	-12.79	-14.42	-20.09	-36.28
	(-9.74)	(-6.22)	(-8.39)	(-6.83)	(-3.00)
Adj R^2	0.20	0.16	0.15	0.26	0.22
Panel B: Arithmetic returns					
Intercept	-0.13	-0.00	0.10	-0.11	-1.18
	(-0.67)	(-0.01)	(0.32)	(-0.44)	(-1.06)
ret_{option}	0.77	0.56	0.76	0.80	0.89
	(-2.29)	(-3.34)	(-1.14)	(-1.28)	(-0.50)
Δr^{10}	-16.40	-12.19	-12.92	-17.65	-28.80
	(-8.34)	(-6.20)	(-7.67)	(-5.60)	(-2.26)
Adj R^2	0.21	0.17	0.17	0.26	0.24
Panel C: Midpoint percentage returns					
Intercept	4.87	1.29	3.51	4.56	15.15
	(6.67)	(2.44)	(3.03)	(6.09)	(4.14)
ret_{option}	1.02	0.60	1.08	0.96	1.52
	(0.11)	(-1.95)	(0.21)	(-0.31)	(1.47)
Δr^{10}	-22.65	-13.95	-18.05	-24.48	-42.05
	(-11.31)	(-7.51)	(-8.30)	(-8.13)	(-3.65)
Adj R^2	0.16	0.14	0.11	0.20	0.23
Nobs	125.22	131.54	128.44	123.77	112.00

Table 7: **Hedging effectiveness**

This table reports the root mean square error (RMSE) in U.S. dollars of the hedging error for an equally weighted portfolio of CDS contracts across each rating category and for the whole sample of firms. Each CDS portfolio is hedged dynamically using equity put options. Hedging is based on empirical hedge ratios as from Equation (4) as well as theoretical hedge ratios computed as from Equation (3). Positions are rebalanced each month. We also report the RMSE of an unhedged CDS portfolio. Panel A reports RMSE values for the full sample period. Panel B shows results for an out-of-sample analysis where empirical hedge ratios are based on estimated coefficients from monthly rolling regressions using a rolling window of four years of monthly data.

	Unhedged	**Model**		**Empirical**	
	$RMSE_u$	$RMSE_h$	$\frac{RMSE_h}{RMSE_u} - 1$	$RMSE_h$	$\frac{RMSE_h}{RMSE_u} - 1$
Panel A: In-sample analysis					
All	68,802	49,163	-0.29	51,530	-0.25
AAA-AA	35,176	33,753	-0.04	32,615	-0.07
A	66,127	50,106	-0.24	56,464	-0.15
BBB	75,144	57,394	-0.24	62,457	-0.17
BB	121,199	101,097	-0.17	238,304	0.97
Panel B: Out-of-sample analysis					
All	78,103	56,683	-0.31	65,314	-0.16
AAA-AA	41,688	39,147	-0.06	39,415	-0.05
A	75,631	54,814	-0.28	69,370	-0.08
BBB	82,886	60,496	-0.27	74,415	-0.10
BB	125,938	92,384	-0.27	127,381	0.01

Table 8: **Other Determinants of Credit Spreads**

This table reports the results of regressing CDS spread changes on put option returns, Treasury rate changes and other determinants of credit spreads during the period August 2001-June 2014. Average regression coefficients from firm-by-firm time-series regressions are reported. The t-statistics are provided in parenthesis and calculated in the same way as in Collin-Dufresne et al. *(2001).* Δr^{10} *is the change in the 10-year constant maturity U.S. Treasury bond rate.* ret_{option} *is the dollar return on the put option.* $\Delta Slope$ *is the change in the slope of the term structure (defined as the difference between the 10-year and the 2-year Treasury rates).* $S\&P$ *is the return on the S&P 500 index.* ΔVIX *is the change in the VIX index of implied volatility of options on the S&P 100 index. Nobs is the average number of observations for each CDS portfolio.*

	All	AAA-AA	A	BBB	BB
Intercept	0.27	0.01	0.08	0.91	-1.23
	(1.28)	(0.04)	(0.41)	(2.16)	(-1.51)
ret_{option}	3.36	0.66	2.41	3.87	7.94
	(5.04)	(0.89)	(3.45)	(3.20)	(2.47)
Δr^{10}	-5.44	-8.45	-3.98	-2.31	-19.33
	(-1.68)	(-4.66)	(-1.98)	(-0.32)	(-1.83)
$\Delta Slope$	0.51	0.18	2.79	-4.90	13.92
	(0.11)	(0.06)	(0.73)	(-0.49)	(1.21)
$S\&P$	-1.61	-0.66	-0.89	-2.20	-2.96
	(-7.57)	(-4.86)	(-5.20)	(-5.41)	(-3.26)
ΔVIX	0.72	0.04	0.95	0.40	1.95
	(4.03)	(0.19)	(2.83)	(1.63)	(3.10)
Adj R^2	0.29	0.26	0.25	0.31	0.34
Nobs	125.22	131.54	128.44	123.77	112.00

Table 9: **Regression of CDS changes on stock returns**

This table reports the results of regressing CDS spread changes on stock returns and Treasury rate changes during the period August 2001-June 2014. In Panel A, we estimate the following time-series regression for each firm j:

$$\Delta CDS_{j,t} = \alpha_j + \beta_{j,S} ret_{stock_{j,t}} + \beta_{j,r} \Delta r_t^{10} + \epsilon_{j,t}$$

In Panel B, we estimate the following time-series regression for each firm j:

$$\Delta CDS_{j,t} = \alpha_j + \alpha_{j,S} hr_{S_{s,t}}(\sigma^A_{IMP}) ret_{stock_{j,t}} + \beta_{j,r} \Delta r_t^{10} + \epsilon_{j,t}$$

where $hr_{S_{s,t}}$ is the mean theoretical hedge ratio at time t for all reference entities in rating s and σ^A_{IMP} is estimated according to Equation (6). If Merton (1974)'s model hedge ratios are accurate, we would expect to estimate a value of $\alpha_{j,S}$ not statistically different from one. The average regression coefficients from the time-series regressions are reported. The t-statistics are provided in parenthesis and calculated in the same way as in Collin-Dufresne et al. *(2001). Δr_t^{10} is the change in the 10-year constant maturity U.S. Treasury bond rate. $ret_{stock_{j,t}}$ is the the stock log-return (in percentage). The t-statistics for $\alpha_{j,O}$ are with respect to the difference from unity. All coefficients are in basis points. Nobs is the average number of observations for each CDS portfolio.*

	All	AAA-AA	A	BBB	BB
	Panel A: Empirical sensitivities				
Intercept	0.16	0.13	0.39	0.30	-1.21
	(1.12)	(1.68)	(2.24)	(1.41)	(-1.62)
ret_{stock}	-1.44	-0.63	-1.24	-1.61	-2.43
	(-11.08)	(-3.66)	(-5.91)	(-7.80)	(-5.86)
Δr^{10}	-10.62	-8.09	-4.90	-10.97	-32.54
	(-5.95)	(-3.95)	(-2.33)	(-4.09)	(-3.66)
Adj R^2	0.25	0.20	0.21	0.27	0.32
	Panel B: Hedge ratio regressions				
Intercept	-0.55	-0.14	-0.30	-0.51	-2.05
	(-4.62)	(-2.85)	(-2.43)	(-3.67)	(-2.60)
ret_{stock}	1.01	1.12	0.94	1.02	1.13
	(0.16)	(0.33)	(-0.40)	(0.15)	(0.66)
Δr^{10}	-17.52	-8.78	-12.52	-18.46	-41.91
	(-8.96)	(-4.04)	(-5.40)	(-6.55)	(-4.21)
Adj R^2	0.25	0.23	0.19	0.28	0.30
Nobs	125.22	131.54	128.44	123.77	112.00

Table 10: **Hedging effectiveness of stocks and industry approach with puts**

This table reports the root mean square error (RMSE) in U.S. dollars of the hedging error for an equally weighted portfolio of CDS contracts across each rating category and for the whole sample of firms. Each CDS portfolio is hedged dynamically using the equity market (Panel A) and equity put options (Panel B). In Panel A, hedging is based on empirical hedge ratios as from Equation (4) but where option returns are replaced by stock returns as well as theoretical hedge ratios computed as from Equation (10). In Panel B, hedge ratios are computed as from Equation (12) and based on an industry application as described in JPMorgan (2006). Positions are rebalanced each month. We also report the RMSE of an unhedged CDS portfolio. RMSE values are for the full sample period.

	Unhedged	**Model**		**Empirical**	
	$RMSE_u$	$RMSE_h$	$\frac{RMSE_h}{RMSE_u}-1$	$RMSE_h$	$\frac{RMSE_h}{RMSE_u}-1$
		Panel A: Hedging with stocks			
All	70,550	59,621	-0.15	54,796	-0.22
AAA-AA	35,427	30,997	-0.13	29,662	-0.16
A	65,502	55,868	-0.15	52,299	-0.20
BBB	74,686	61,515	-0.18	51,904	-0.31
BB	125,148	94,462	-0.25	83,221	-0.34
		Panel B: Hedging with puts - industry approach			
All	68,802	110,785	0.61	-	-
AAA-AA	35,176	92,666	1.63	-	-
A	66,127	99,948	0.51	-	-
BBB	75,144	144,761	0.93	-	-
BB	121,199	281,595	1.32	-	-

Table 11: **Hedging costs**

This table reports the costs of hedging under three alternative hedging strategies: hedging with put options using the industry approach as described in JPMorgan (2006); hedging with put options using our theoretical hedge ratios computed as from Equation (3); hedging with stocks using theoretical hedge ratios as defined in Equation (10). Mean theoretical hedge ratios of each CDS portfolio (expressed in basis points) are converted into dollar amounts by multiplying them by the average duration of the CDS portfolio. Industry hedge ratios provide the number of put options contracts to purchase and are converted into dollar amounts by multiplying them by the average put price of each CDS portfolio. Hedging costs are reported in U.S. dollars. The number of shares or put options required by the hedging strategies are also reported.

	Industry		**Model**		**Model**	
	Put hedge	*No. puts*	*Put hedge*	*No. puts*	*Stock hedge*	*No. shares*
All	88,840	1,710	16,629	272	260,439	6,257
AAA-AA	74,032	1,256	8,509	151	167,350	3,436
A	73,238	1,466	13,474	230	229,944	5,135
BBB	98,729	1,840	17,686	274	254,454	6,706
BB	130,220	3,048	34,798	727	505,887	22,044

Appendix

A Deriving Hedge Ratios of Credit Spreads to Equity Options

In this section we show how to derive theoretical hedge ratios of credit spreads to equity options. First, we define the hedge ratio based on put options, hr_P:

$$hr_P = \frac{\partial CS}{\partial P} P \tag{A.1}$$

where CS and P represent the credit spread and the put option price, respectively. ∂ is the partial derivative symbol.

Merton (1974) and Geske (1979) express corporate debt prices and equity option prices as a function of a firm's asset value, respectively.

In particular, Merton (1974) shows that corporate debt of face value D is equal to risk-free debt discounted at the risk-free rate r minus a European put option on the firm's asset value V with asset returns' volatility σ_V. The corporate bond yield spread of maturity τ can be expressed as:

$$CS(\tau) = -\frac{1}{\tau} \ln\left(\Phi[h_2(d, \sigma_V^2 \tau)] + \frac{1}{d} \Phi[h_1(d, \sigma_V^2 \tau)] \right) \tag{A.2}$$

where $\Phi[\cdot]$ is the univariate cumulative normal distribution function and

$$d = \frac{De^{-r\tau}}{V}$$

$$h_1(d, \sigma_V^2 \tau) = \frac{-(\sigma_V^2 \tau/2 - \ln(d))}{\sigma_V \sqrt{\tau}}$$

$$h_2(d, \sigma_V^2 \tau) = \frac{-(\sigma_V^2 \tau/2 + \ln(d))}{\sigma_V \sqrt{\tau}}$$

Geske (1979) shows that an equity option can be regarded as an option on an option on the firm's asset value (compound option). For the case of a put option of maturity τ_1 with strike price K, P would be equal to the following expression:

$$\begin{aligned} P &= De^{-r\tau}\Theta[-h_3(\bar{d},\sigma_V^2\tau_1), h_2(d,\sigma_V^2\tau); -\sqrt{\tau_1/\tau}] \qquad \text{(A.3)} \\ &\quad -V\Theta[-(h_3(\bar{d},\sigma_V^2\tau_1)+\sigma_V\sqrt{\tau_1}), h_1(d,\sigma_V^2\tau); -\sqrt{\tau_1/\tau}] + Ke^{-r\tau_1}\Phi[-h_3(\bar{d},\sigma_V^2\tau_1)] \end{aligned}$$

where $\Theta[\cdot]$ is the bivariate cumulative normal distribution function and

$$\bar{d} = \frac{\bar{V}e^{-r\tau_1}}{V}$$

$$h_3(\bar{d},\sigma_V^2\tau_1) = \frac{-(\sigma_V^2\tau_1/2 + \ln(\bar{d}))}{\sigma_V\sqrt{\tau_1}}$$

$\bar{V}$ is the value of V where the option is just at the money at time τ_1 and is the solution to the following equation:

$$V\Phi[h_2(d,\sigma_V^2\tau) + \sigma_V\sqrt{\tau-\tau_1}] - De^{-r(\tau-\tau_1)}\Phi[h_2(d,\sigma_V^2\tau)] - K = 0$$

Given the dependence of both the credit spread and the put option price on the firm's asset value V as well as the fact that the equity can be regarded as a European call option on the firm's asset, we can now re-write Equation (A.1) as the product of three partial derivatives:

$$hr_P = \frac{\partial CS}{\partial P}P = \frac{\partial CS}{\partial V}\frac{\partial V}{\partial P}P = \frac{\partial CS}{\partial V}\frac{\partial V}{\partial E}\frac{\partial E}{\partial P}P \qquad \text{(A.4)}$$

We start by deriving the first partial derivative of the credit spread with respect to V. This gives:

$$\frac{\partial CS}{\partial V} = -\frac{1}{\tau}\frac{\frac{\phi[h_2(d,\sigma_V^2\tau)]}{V\sigma_V\sqrt{\tau}} + \frac{1}{De^{-r\tau}}(\Phi[h_1(d,\sigma_V^2\tau)] - \frac{\phi[h_1(d,\sigma_V^2\tau)]}{\sigma_V\sqrt{\tau}})}{\Phi[h_2(d,\sigma_V^2\tau)] + \frac{1}{d}\Phi[h_1(d,\sigma_V^2\tau)]} \qquad \text{(A.5)}$$

where $\phi[\cdot]$ is the univariate normal density function.

Under Merton (1974), the equity value of a firm is a European call option on the asset value V:

$$E = V\Phi[h_1(d, \sigma_V^2 \tau)] - De^{-r\tau}\Phi[h_2(d, \sigma_V^2 \tau)] \tag{A.6}$$

We use this insight to compute the second partial derivative and obtain the following:

$$\frac{\partial V}{\partial E} = \frac{1}{\Phi[h_1(d, \sigma_V^2 \tau)]} \tag{A.7}$$

In order to compute the third partial derivative, we first express the equity value as a function of the option price. To this end, we solve for D in Equation (A.3), plug it in Equation (A.6) and obtain the following:

$$\begin{aligned} E &= V\Phi[h_1(d, \sigma_V^2 \tau)] - e^{-r\tau}\Phi[h_2(d, \sigma_V^2 \tau)] \\ &\quad \frac{P + V\Theta[-(h_3(\bar{d}, \sigma_V^2 \tau_1) + \sigma_V \sqrt{\tau_1}), h_1(d, \sigma_V^2 \tau); -\sqrt{\tau_1/\tau}] - Ke^{-r\tau_1}\Phi[-h_3(\bar{d}, \sigma_V^2 \tau_1)]}{e^{-r\tau}\Theta[-h_3(\bar{d}, \sigma_V^2 \tau_1), h_2(d, \sigma_V^2 \tau); -\sqrt{\tau_1/\tau}]} \end{aligned} \tag{A.8}$$

Next we compute the partial derivative of the equity value with respect to the option price and obtain:

$$\frac{\partial E}{\partial P} = -\frac{\Phi[h_2(d, \sigma_V^2 \tau)]}{\Theta[-h_3(\bar{d}, \sigma_V^2 \tau_1), h_2(d, \sigma_V^2 \tau); -\sqrt{\tau_1/\tau}]} \tag{A.9}$$

We can now group the solutions to the three partial derivatives as from Equations (A.5), (A.7) and (A.9) to compute the final hedge ratio:

$$\begin{aligned} hr_P &= \frac{\partial CS}{\partial P} P = -\frac{1}{\tau} \frac{\frac{\phi[h_2(d, \sigma_V^2 \tau)]}{V\sigma_V\sqrt{\tau}} + \frac{1}{De^{-r\tau}}(\Phi[h_1(d, \sigma_V^2 \tau)] - \frac{\phi[h_1(d, \sigma_V^2 \tau)]}{\sigma_V\sqrt{\tau}})}{\Phi[h_2(d, \sigma_V^2 \tau)] + \frac{1}{d}\Phi[h_1(d, \sigma_V^2 \tau)]} \\ &\quad \frac{-\Phi[h_2(d, \sigma_V^2 \tau)]}{\Phi[h_1(d, \sigma_V^2 \tau)]\Theta[-h_3(\bar{d}, \sigma_V^2 \tau_1), h_2(d, \sigma_V^2 \tau); -\sqrt{\tau_1/\tau}]} P \end{aligned} \tag{A.10}$$