Great in practice, not in theory: An empirical examination of covered call writing

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Practical applications

Covered call writing is a common investment approach among individual investors and money managers. Although these investors often argue for the practice on the grounds that income from covered call writing can enhance overall returns during periods when stock prices are languishing, it had not been previously demonstrated that the practice is empirically supported. The practical application of this paper is that it provides an empirical grounding that investors can use when deciding on the merits of a covered call writing investment strategy.

Abstract

We examine the empirical performance of an investment strategy that uses covered call writing to enhance the income from long positions in 27 stocks that are included in the FT-SE 100 Index. Using data for the period January 1994–December 1999 we show that, contrary to theory, in most instances covered call positions generate returns that exceed returns generated by buy-and-hold strategies.

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INTRODUCTION

There are various mutual funds in existence[1] that claim to enhance returns to unit holders through writing call options on investments held in the funds. This strategy is called 'covered call writing' when the number of options written on a stock does not exceed the number of shares of that stock held in the portfolio. Proponents of the covered call strategy assert that the portfolio benefits from a price increase[2] and the call premium under conditions when the stock is called out, and benefits from the call premium if the stock is not called out. In the latter instance,

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income from writing the call mitigates the drag on returns due to stagnancy or decline in the price of a portfolio member.

While these arguments are superficially appealing, closer inspection suggests that covered call writing may militate against enhancing portfolio returns. To see this, think of a covered call position as a portfolio comprised of a long position in the underlying financed in part by a short position in an option on the same underlying. Using a and b to denote positive portfolio weights where a is greater than 1, and $a-b=1$, the initial condition is the following:

$$\underbrace{aS_t - bC_t}_{\text{Covered Call}} = \underbrace{S_t}_{\text{Buy and Hold}} \quad (1)$$

where S_t is the price of the underlying asset and C_t is the price of the call. In a Black and Scholes[3,4] world, the option can be replicated using a long position in δ_t units of the underlying asset, where $0<\delta_t<1$, and a short position in a riskless bond so that:

$$C_t = \delta_t S_t - B_t \quad (2)$$

Substituting the expression in (2) into (1) gives:

$$aS_t - b(\delta_t S_t - B_t) = (a - \delta_t b)S_t + bB_t \quad (3)$$

The expression in (3) indicates that entering a covered call position amounts to increasing one's position in a riskless bond in substitution for the underlying. In most cases one would think of the expected return on the underlying exceeding the return on the riskless bond, so writing covered calls typically would reduce expected returns.

MONTE CARLO SIMULATION

To illustrate the case in which the expected return on the underlying exceeds the return on the riskless bond ($E[r_i]>r_f$), we constructed a 50,000 path Monte Carlo simulation using five economic specifications. The economies are the Black–Scholes[3] economy (BS), the Cox[5] constant elasticity of variance economy (CEV), the Geske[6] compound option-pricing model (LEV), the Merton[7] jump-diffusion economy (JD), and the Heston[8] stochastic volatility economy (HES). Details of each of these economies are presented in the Appendix. In each of these economies, we adopted covered call strategies using options with, respectively, 30, 60, and 90 days to maturity.

We chose model parameters, shown in Table 1, so that in each economy the price of a 30-day, at-the-money European style call option approximated the Black–Scholes price with volatility set at 15 per cent. In Table 1, the percentages associated with strike prices K_1 and K_2 denote the degree of moneyness[9] at which the near-the-money and out-of-the-money options were written in the simulations. Note that the comparison of covered call strategies to the buy-and-hold strategies in this paper are all 'within model' and not 'across models' so it is not necessary to establish a correspondence between models that goes beyond the qualitative similarity implied by the above approach.

As set out in Figure 1, the pattern of covered call writing we adopted in the simulations matches the pattern that is feasible using transactions data. Although Monte Carlo simulations permit one to assume the existence of options with any desired maturities, we elected to render our simulations consistent with the coverage pattern that can be achieved with transactions data. For the stocks included in this study (see Table 4 below), option prices were quoted for options with 90-day increments in time to maturity. This permitted the coverage pattern for written calls that is shown in Figure 1. For example, in the 30-day written call protocol,

Table 1: Parameter values

	Economies				
	Black–Scholes	*Leveraged*	*CEV*	*Heston*	*Jump/Diffusion*
S_0	100	100	100	100	100
V	—	150	—	—	—
$M(t,T)$	—	50	—	—	—
$T\text{-}t$	—	10 years	—	—	—
K_1	102%	102%	102%	102%	102%
K_2	105%	105%	105%	105%	105%
μ	0.12	0.095	0.12	0.12	0.12
R	0.05	0.05	0.05	0.05	0.05
Q	0	0	0	0	0
α	—	—	4/3	—	0.13
$\sqrt{v}$	0.15	0.10	$\sqrt{0.5}$	0.15	$\sqrt{0.16}$
θ	—	—	—	0.15	—
κ	—	—	—	20.0	0
σ	—	—	—	0.10	—
ρ	—	—	—	−0.5	—
λ	—	—	—	—	2 jumps/year
β	—	—	—	—	$\sqrt{0.006}$

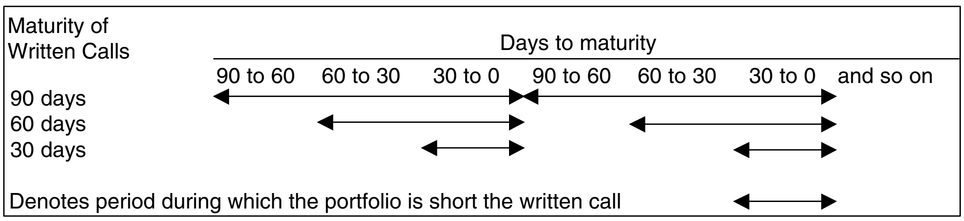

Figure 1: Coverage pattern of written calls

we left the position uncovered (ie no call was written) for 60 days until the shortest maturity call that was quoted on the market had 30 days left to maturity. At this point, we wrote a 30-day call at the quoted market price. In the next 90-day cycle, we followed the same protocol. Similarly, the 60-day options left the covered call position uncovered one-third of the time.

The simulation results are set out in Table 2. In addition to including strategies involving 30, 60, and 90-day options, respectively, we tracked covered call positions for two levels of strike price. In the first case, we assumed that the written option possessed a strike price, K_1, 2 per cent out of the money. In the second case we assumed a strike price, K_2, 5 per cent out of

Table 2: Summary of simulation results

	30 day		*60 day*		*90 day*	
	K_1 (%)	K_2 (%)	K_1 (%)	K_2 (%)	K_1 (%)	K_2 (%)
Panel A: Covered call returns as a percent of buy-and-hold returns						
BS	93.7	98.7	84.8	93.9	75.5	87.3
CEV	93.7	98.9	84.4	94.5	74.5	87.9
LEV	94.1	98.9	85.5	94.6	76.6	88.5
JD	94.2	99.3	85.6	94.8	76.4	88.2
HES	93.5	98.8	84.0	93.9	74.0	86.8
Panel B: Covered call volatility as a percent of buy-and-hold volatility						
BS	90.2	97.5	75.8	88.7	55.6	75.6
CEV	90.7	98.4	75.9	90.7	55.4	78.3
LEV	91.0	98.0	76.8	90.4	56.9	78.2
JD	90.7	96.3	76.7	87.6	58.1	75.1
HES	90.6	97.7	76.9	90.0	57.6	77.8

Table 3: Percentage of paths with covered call returns in excess of buy-and-hold returns

	90 day	
	K_1 (%)	K_2 (%)
BS	21	38
CEV	17	39
LEV	22	41
JD	27	41
HES	21	39

the money. The results indicate that in all cases, the mean returns from the covered call positions were less than for the buy-and-hold positions. Also, in all cases, the volatilities of returns from the covered call positions were less than for the buy-and-hold positions.

Table 3 presents data on the frequency with which returns from the covered call positions exceeded returns from the buy-and-hold positions. Notwithstanding the results for the mean shown in Table 2, Table 3 shows that in qualitative terms, the 'losing' covered call strategy outperforms the buy-and-hold strategy relatively frequently. Arguably, participants in a market which exhibits this characteristic could develop a favourable perception of the merits of covered call writing even though it is a losing strategy overall.

DATA

We obtained the data used in this paper from the LIFFE Euro-Out Products tick data disc. We randomly selected 30 companies from among the constituents of the FT-SE 100 Index as on 31st December, 1999. The LIFFE Euro-Out

Products tick data disc includes option price[10] data for a wide variety of traded options along with contemporaneous prices for the underlying. We deleted one company from the study because it was unclear whether a stock split reported by the company had been properly accounted for in the underlying price time series on the data disc.[11] We deleted two companies because of insufficient numbers of quoted option prices. Table 4 sets out the names and stock symbols of the companies included in the study.

Table 5 reports the returns, volatility, and the coefficient of correlation between returns on the individual stocks and the FT-SE 100 Index for the sample data. The reported returns are the annualised log-differences of share price at the beginning and end of the timeframe the study covers. The reported standard deviations of returns are the annualised standard deviations of daily returns over the timeframe the study covers. The reported correlations are also based on daily returns observations.

The coefficients of correlation for all companies were positive. Although a more sophisticated estimation of time varying coefficients of correlation, and a broader definition of the market portfolio would be desirable, the historical coefficients are suggestive of the possibility that each of the stocks is a positive beta stock in a capital asset pricing model sense. This being the case, the return expected on each stock exceeds the return on a riskless bond. Consequently, as shown in (3), our *ex ante* expectation is that mean returns for the buy-and-hold strategies should exceed mean returns for the covered call strategies.[12]

Table 4: Companies included in the sample and related stock symbols

Stock symbol	*Company name*	*Stock symbol*	*Company name*
ALD	Allied Domecq PLC	MS	Marks and Spencer PLC
BBL	Barclays PLC	PO	Peninsular and Oriental Steam Navigation Company PLC
BOT	Boots Company PLC	RTZ	Rio Tinto PLC
BP	British Petroleum Company PLC	RUT	Reuters Holdings PLC
BSS	Bass PLC	RYL	Royal and Sun Alliance Insurance Group PLC
CAD	Cadbury Schweppes PLC	SAN	Sainsbury (J) PLC
CIR	Blue Circle Industries PLC	STL	Corus Group PLC (formerly British Steel PLC)
CUA	Commercial General Union PLC	TAR	Tarmac PLC
CW	Cable and Wireless PLC	TCO	Tesco PLC
DIX	Dixon's Group PLC	TW	Thames Water PLC
GXO	Glaxo Wellcome PLC	ULV	Unilever PLC
HSB	HSBC Holdings PLC	VOD	Vodafone Air Touch PLC
ICI	Imperial Chemical Industries PLC	ZCA	Zeneca Group PLC
LMO	LASMO PLC		

Table 5: *Realised returns, volatilities, and correlation with the FTSE 100 Index*

Company	*Annual returns (%)*	*Volatility (%)*	*Correl. coeff.*	*Company*	*Annual returns (%)*	*Volatility (%)*	*Correl. coeff.*
ALD	−3.43	24.09	0.39	MS	0.35	34.69	0.41
BBL	17.11	29.35	0.65	PO	−7.07	26.51	0.43
BOT	0.35	23.19	0.38	RTZ	7.89	25.02	0.44
BP	20.92	23.65	0.29	RUT	9.51	25.64	0.44
BSS	−1.20	44.85	0.37	RYL	14.63	33.41	0.58
CAD	5.82	26.07	0.37	SAN	5.42	32.95	0.37
CIR	5.60	23.60	0.33	STL	−4.18	26.06	0.28
CUA	0.86	31.45	0.58	TAR	3.94	33.55	0.27
CW	7.19	29.80	0.54	TCO	−5.12	32.56	0.39
DIX	11.30	33.00	0.28	TW	15.92	26.57	0.30
GXO	27.26	32.48	0.60	ULV	4.88	22.15	0.53
HSB	14.86	28.03	0.69	VOD	6.94	24.31	0.52
ICI	16.13	31.86	0.36	ZCA	33.43	33.11	0.50
LMO	−3.03	29.43	0.24				

For each stock in the study, we tracked a buy-and-hold position concurrent with a covered call position. In each case, we did so for three different maturities of written option with the coverage patterns following those described in Figure 1. For each maturity, we tracked a covered call strategy for two levels of moneyness. For the first level, we used options with a strike price out of the money, but nearest to the at-the-money level. For the second level, we used the next available out-of-the-money strike price. We wrote options in a quantity equal to the holdings in the underlying at the beginning of each of the coverage periods shown in Figure 1 and used the option premiums from the written calls to increase the number of units of the underlying in the covered call position. If the stock was called out, we deleted units from our position equal in amount to the number of written calls in the call-out, and used the proceeds from the call-out (strike price times the number of written calls in the call-out) to acquire as many units of the underlying as possible at the price of the underlying at the time of the call-out. At the end of the study period, we calculated the annualised returns for the covered call position and the buy-and-hold position, respectively. We did not take account of transaction costs involved in either investment strategy because the goal of this paper is to examine the comparative properties of the underlying and options on the underlying rather than to determine relative economic merits.

RESULTS AND DISCUSSION

Table 6 summarises our results. In all but one of the scenarios, covered call writing strategies produced better returns more frequently than the buy-and-hold strategy. We consider the

Table 6: Annualised returns from covered call writing compared to the buy-and-hold strategy

	Covered call						
	30 Day		60 Day		90 Day		Buy and Hold
	A (%)	B (%)	A (%)	B (%)	A (%)	B (%)	
Panel A							
ALD	−4.20	−3.12	0.18	−1.34	1.13	−0.47	−3.43
BBL	13.99	15.84	16.55	18.94	7.78	12.34	17.11
BOT	2.45	2.06	4.74	3.00	2.54	1.71	0.35
BP	23.14	23.31	21.90	22.71	20.95	22.63	20.92
BSS	−10.51	−10.88	−1.85	−3.19	−4.96	−3.61	−1.20
CAD	3.25	6.47	8.96	8.30	7.94	8.12	5.82
CIR	7.47	7.79	8.72	9.27	8.70	9.72	5.60
CUA	7.21	3.01	6.29	4.93	7.84	5.34	0.86
CW	5.11	8.36	8.36	9.25	8.60	8.87	7.19
DIX	6.37	8.20	11.36	13.12	7.63	8.95	11.30
GXO	25.46	27.17	22.30	25.03	11.78	16.03	27.26
HSB	13.12	15.88	13.65	15.88	6.91	11.46	14.86
ICI	8.29	11.35	12.76	15.34	6.87	8.66	16.13
LMO	−4.81	−1.17	−0.74	−0.41	−0.39	−1.51	−3.03
MS	4.79	4.30	8.34	6.17	8.24	5.85	0.35
PO	−7.12	−6.99	−5.37	−6.21	−4.61	−6.51	−7.07
RTZ	8.53	10.81	11.79	12.01	8.03	10.40	7.89
RUT	6.89	8.67	6.57	7.72	6.01	8.33	9.51
RYL	18.58	16.53	21.91	20.78	18.06	18.32	14.63
SAN	3.67	7.25	7.81	8.92	4.16	5.97	5.42
STL	−3.49	−3.83	−1.05	−0.88	−0.11	−2.25	−4.18
TAR	1.06	2.50	5.41	6.81	8.97	8.14	3.94
TCO	2.48	−1.28	0.34	−0.28	0.45	−0.79	−5.12
TW	19.72	18.31	18.38	18.90	19.38	20.40	15.92
ULV	2.51	4.28	3.83	3.70	4.04	4.55	4.88
VOD	10.75	8.72	7.20	8.77	6.53	7.71	6.94
ZCA	30.39	33.91	23.06	28.18	22.99	25.10	33.43
Panel B							
VWP	10.93	11.90	11.82	12.78	9.26	10.42	11.50
EWP	10.35	11.45	10.83	11.90	8.75	9.81	10.95
Panel C							
Winners	11	19	19	21	16	18	

A denotes the nearest the money strategy, and B denotes the next-nearest the money strategy.

statistical significance of these outcomes using the 'sign test for matched pairs' and the 'Wilcoxon signed rank test'. These statistical methods and the expression of the null hypothesis in the context of them are discussed below.[13,14]

The sign test for matched pairs applies in situations in which there is either a failure or a success arising from repeated independent trials and there is a constant probability, p, of success. The test permits inference about the hypothesised probability, p. In the current context, the trials are the attempts to earn superior returns through the buy-and-hold strategy versus the covered call strategy. One would hypothesise that, if each strategy is equally effective, there would be an equal chance that one strategy would outperform the other at each comparison point. Thus, in the context of the sign test for matched pairs, the null hypothesis is the following:

H_0: The probability that buy and hold outperforms covered call writing for each attempt is $\frac{1}{2}$.

The assumptions underlying the test are the following:

1 the outcomes can be classified as a success or a failure
2 the probability of a success remains constant from trial to trial and
3 the trials are independent.

There were no ties in the tests. The null hypothesis is that the probability of a success or failure is equal for each comparison of investment protocols. The hypothesised probability is, therefore, constant.

For larger samples (N>20), the test statistic z for the sign test for matched pairs can be determined in relation to either P_M, where P_M is the number of occurrences of the more frequent outcome divided by the number of trials N, or in relation to P_L, where P_L is the number of occurrences of the less frequent outcome divided by the number of trials N. There are therefore two possible z-scores, Z_M determined using P_M, and Z_L determined using P_L. It is easy to show that for hypothesised $p=\frac{1}{2}$, $z_M=-z_L$ so, from an inference point of view, and consistent with the two-sided hypothesis stated above, it makes no difference whether one bases the statistical test on P_M or P_L. The sole effect of basing the z-score calculation on P_M versus P_L is that in the first instance the correction for continuity in the z-score calculation is $-\frac{1}{2}N$, whereas in the second instance it is $+\frac{1}{2}N$. Expressions for both possible z-scores are set out below:

$$z_M = \frac{(P_M - p) - 1/2N}{\sqrt{pq/N}}$$
$$z_L = \frac{(P_L - p) + 1/2N}{\sqrt{pq/N}} \quad (4)$$

In equations (4), z_M and z_L are the usual z-score associated with the unit normal distribution. p is the hypothesised probability, and q is $1-p$. The probability associated with the test statistic $z_M(z_L)$ is interpreted as the probability that P_M or greater (P_L or less) was obtained by chance given a true probability p equal to its hypothesised value.

The Wilcoxon signed rank test is also a test for population differences in matched pairs. It takes account not only of the number of occurrences of a particular outcome but also takes account of the rank of the absolute size of each difference. This test, therefore, uses more information from a particular test than the sign test for matched pairs. As in the preceding case, comparison of individual returns performance is between the buy-and-hold strategy and the covered call strategy.

The assumptions underlying the Wilcoxon signed rank test are the following:

1 Define Z_i such that $Z_i \equiv r_{CC} - r_{B\&H}$, where $r_{B\&H}$ denotes returns from the buy-and-hold strategy and r_{CC} denotes returns from the covered call strategy, both in respect of stock i. The assumed underlying model is:

$$Z_i = \theta + e_i \tag{5}$$

In (5), θ is the hypothesised differential in investment strategies and the e_i are unobservable random variables.

2 The unobservable random variables e_i are mutually independent.

3 Each e_i comes from a continuous population that is symmetric about zero. The populations do not need to be identical.

The null hypothesis in the context of the Wilcoxon signed rank test is:

$$H_0 : \theta = 0$$

To calculate the test statistic T, rank[15] the absolute values of Z_i so that there is a rank value R_i corresponding to each Z_i. Define the indicator variable ψ_i to equal one if Z_i is positive and zero otherwise. If $\sum \psi_i < \sum (1 - \psi_i)$, the test statistic T is $\sum R_i \psi_i$. Otherwise, it is $\sum R_i (1 - \psi_i)$

For large samples, T is normally distributed with:

$$E[T] = \frac{N(N+1)}{4} \tag{6}$$

and

$$\text{VAR}[T] = \frac{N(N+1)(2N+1)}{24} \tag{7}$$

The test score is:

$$z = \frac{T - E[T]}{\sqrt{\text{VAR}[T]}} \tag{8}$$

In (7), T is the test statistic calculated as described above. In (8), z is the usual z-score associated with the unit normal distribution. If z is less than (greater than) zero, the probability associated with the test statistic z is interpreted as the probability of obtaining the test statistic or less (or more) given that the populations of returns differentials are symmetrical with identical median.

As with the sign test for matched pairs, inferences are identical whether the test statistic z is determined from T calculated using the less frequently occurring outcome, as above, or if z is determined from T calculated using the more frequently occurring outcome. As a consequence, and consistent with the two-sided nature of the hypothesis stated above, one need not make an *ex ante* selection of a 'preferred' or 'winning' investment protocol to calculate the test statistic. Define T_L equal to T calculated using the less frequently occurring outcome, T_M equal to T calculated using the more frequently occurring outcome, and corresponding z-scores z_L and z_M. It can be shown that $z_L = -z_M$. This being the case, there can be no difference in inference in relation to the two-sided hypothesis stated above resulting from calculating z_L rather than z_M, or vice versa.

Given all of the assumptions set out above, the Wilcoxon signed rank test constitutes a test for location. If the error terms cannot be assumed to be symmetrically distributed, the Wilcoxon signed rank test constitutes a joint test for the median and for symmetry (cf. Gibbons and Chakraborti,[16] pp. 168–169). In this circumstance, the null hypothesis in the context of the Wilcoxon signed rank test is:

H_0: The population of differences in investment protocols is symmetric with median $\theta = 0$.

If the joint null hypothesis stated above is rejected, it is not possible to determine whether the failure is attributable to one or both elements of the null hypothesis.

To facilitate discussion, we arbitrarily use the term winner to identify cases where returns from covered call writing exceed returns from the buy-and-hold strategy. The column headings A and B in Table 7 denote, respectively, the nearest the money option and the next-nearest the money option. Panel A in Table 7 summarises the results of the sign test for matched pairs. The results for 30-day options next-nearest the money, and 60-day options both nearest and next-nearest the money, and 90-day options next-nearest the money indicate that the covered call writing strategy produced an unusual number of winners. The results for 60-day options next-nearest the money indicate that the probability that the realised number of winners occurred by chance conditional on an hypothesised probability of 50 per cent was just 0.4 per cent. These results suggest that the hypothesis under the sign test for matched pairs is not supported by the data for at least some of the covered call writing protocols.

Panel B of Table 7 summarises the results for the Wilcoxon signed rank test. In each case the test statistic z is negative. The probability associated with the test statistic z is interpreted as the probability of obtaining the test statistic or less given that the populations of returns differentials are symmetrical with identical median. For the most part, the results in Panel B support those obtained in Panel A with the possible exception of the result for 90-day next-nearest the money. The test result under the

Table 7: Results of statistical tests

	30 Day		*60 Day*		*90 Day*	
	A	*B*	*A*	*B*	*A*	*B*
Panel A: Sign test for matched pairs						
Winners	11	19	19	21	16	18
Losers	16	8	8	6	11	9
Max	16	19	19	21	16	18
z	0.7698	1.9245	1.9245	2.6943	0.7698	1.5396
p-value	0.221	0.027	0.027	0.004	0.221	0.062
Panel B: Wilcoxon signed rank test						
T	168	115	102	58	182	148
z	−0.5045	−1.7778	−2.0902	−3.1473	−0.1682	−0.9850
p-value	0.307	0.038	0.018	0.001	0.433	0.162

latter test is less extreme than for the former test. The difficulty with the Wilcoxon signed rank test is that its interpretation is unclear if the error terms in the model cannot be assumed symmetrically distributed. The stylised facts of returns distributions suggest that there is the possibility of asymmetrically distributed stock returns. This therefore calls into question whether the hypothesis fails due to asymmetry or due to a median $\theta \neq 0$.

CONCLUSIONS AND FUTURE RESEARCH

In this paper, we present results of a comparison of two investment protocols. In the first instance, the investment protocol involves a buy-and-hold strategy. In the second instance, it involves writing covered calls on a long position in an underlying stock. We conduct the comparison in synthesised economies to demonstrate the likely outcome if the real economy were consistent with the theoretical models in the synthesised economies. We also conduct the comparison using transactions data. In the latter case, we find a surprising number of cases in which the covered call strategy produces greater returns than the buy-and-hold strategy, with some evidence that this outcome is statistically significant. This result is surprising considering the clear evidence in the synthesised economies that this result does not occur when tested over many repeated trials. The evidence from the synthesised economies indicates, however, that even though the buy-and-hold strategy produces greater returns when an average is taken over many repeated trials, a qualitative assessment of the covered call strategy suggests it performs well relatively frequently.

References and Notes

1 cf. the PRO-AMS, PRO-AMS US, and Triax CARTS funds, for example.
2 In practice, covered call writing involves writing options that are somewhat out-of-the-money.
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4 We recognise that there are various limitations of the Black–Scholes pricing approach, but we submit that the approach is qualitatively appropriate in this instance.
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9 By moneyness, we mean the extent to which the option is out of the money.
10 Prices are in respect of American style options. Although the options used in the study possessed the early exercise feature, there is no evidence to suggest that early exercise occurred during the life of these options.
11 We also calculated results including this company and our best estimate of appropriate treatment for the apparent stock split. There was no material difference in the conclusions of the study.
12 Since both strategies include a long position in the underlying, we did not explicitly take account of dividends in the cash flows arising from each of the respective positions.
13 Hollander, M. and Wolfe, D.A. (1973) 'Nonparametric Statistical Methods', John Wiley & Sons, New York.
14 Hollander and Wolfe[13] present and explain both of the statistical methods used in this paper. The comments on the statistical methods in this section follow the comments and analysis in their Chapters 2 and 3.
15 The ranking is in ascending order so that the smallest absolute value receives a rank of one.
16 Gibbons, J.D. and Chakraborti, S. (1992) 'Nonparametric Statistical Inference, 3rd edn. Marcel Dekker, Inc, New York.

Appendix 1

BLACK–SCHOLES

In this model, the price of the underlying asset S is assumed to follow the stochastic process:

$$dS = \mu S dt + \sigma S dZ \qquad (A1)$$

The discrete time version of (A1) is:

$$S(t_{i+1}) = S(t_i)\exp[(\mu - \nu/2)\Delta t + (\sqrt{\nu}x\sqrt{\Delta t})] \qquad (A2)$$

where x is a random draw from the unit normal distribution.

LEVERAGED MODEL

The Geske[6] compound option pricing model is used to model option pricing in the context of a firm with financial leverage. Geske[6] assumes that firm value, V, follows the stochastic process:

$$dV = \mu V dt + \sqrt{\nu} V dZ \qquad (A3)$$

He also assumes that the firm has issued a pure discount bond that gives the holder the right to amount M at maturity T. Denote its value at the present time t by $M(t, T)$ and at maturity by $M(T, T)$. The firm is not permitted to issue *pari passu* or senior ranking claims, nor is it permitted to make distributions or share repurchases prior to T. Under this specification, the bondholders can be viewed as 'owning' the firm with the common shareholders having an option to acquire ownership at T upon payment to the bondholders of the amount $M(T, T)$. A call option on a common share is therefore an option on an option. Geske[6] shows that the value of a common share, S, is given by the Black–Scholes call-option pricing formula and develops a pricing expression for the value of a call option on S.

The following is the discrete time version of (A3):

$$V(t_{i+1}) = V(t_i)\exp\left[(\mu - \nu/2)\Delta t + (\sqrt{\nu}\,x\sqrt{\Delta t})\right] \qquad (A4)$$

where x is a random draw from the unit normal distribution.

CONSTANT ELASTICITY OF VARIANCE

The CEV model[5] is distinguished by its assumption that the underlying follows the stochastic process:

$$dS = \mu S dt + \sqrt{\nu} S^{\alpha/2} dZ \qquad (A5)$$

The discrete time version of (A5) is:

$$S(t_{i+1}) = S(t_i) + \mu S(t_i)\Delta t + \sqrt{\nu}\, S(t_i)^{\beta-2/2}\sqrt{\Delta t}\, x \qquad (A6)$$

where x is a random draw from the unit normal distribution.

STOCHASTIC VOLATILITY

Heston[8] (see also Knoch, 1992) specifies geometric Brownian motion for the underlying and a square root process with a mean reversion term for the volatility parameter as follows:

$$dS = \mu S dt + \sqrt{\nu} S dZ_1 \qquad (A7)$$

$$d\nu = \kappa[\theta - \nu]dt + \sigma\sqrt{\nu} dZ_2 \qquad (A8)$$

Here, μ, κ, θ, and σ are constants and dZ_1 and dZ_2 are standard Wiener processes whose increments have instantaneous correlation ρ. The discrete time versions of (A7) and (A8) are:

$$S(t_{i+1}) = S(t_i)\exp[(\mu - \nu(t_i)/2)\Delta t + (\sqrt{\nu(t_i)}\, x_1\sqrt{\Delta t})] \qquad (A9)$$

and,

$$\nu(t_{i+1}) = \nu(t_i) + \kappa(\theta - \nu(t_i))\Delta t + (\sigma\sqrt{\nu(t_i)}x_2\sqrt{\Delta t}) \quad \text{(A10)}$$

where x_1 and x_2 are determined by a random draw from the bivariate normal distribution with mean zero, unit variance, and correlation coefficient ρ.

JUMP-DIFFUSION

Merton's[7] model is based on geometric Brownian motion augmented by a Poisson process. He thinks of the Poisson distributed event as the arrival of important information about the stock that affects its price. He assumes arrivals are independently and identically distributed. The probability of an event occurring during an interval of time h, where h can be arbitrarily small, can be described as follows:

Pr{event does not occur in the time interval $(t,\ t+h)\} = 1 - \lambda h + O(h)$,
Pr{event occurs once in the time interval $(t,\ t+h)\} = \lambda h + O(h)$,
Pr{event occurs more than once in the time interval $(t,\ t+h)\} = O(h)$ (A11)

where $O(h)$ is the asymptotic order symbol defined by $\psi(h) = O(h)$ if $\lim_{h\to 0}[\psi(h)/h]$ is equal to zero, and λ is the mean number of arrivals per unit of time. If a Poisson event occurs, the effect on the price of the stock is SY where Y is a drawing of a random variable Y from a distribution where all Y are greater than or equal to zero, and successive draws of the random variable Y are independently and identically distributed. The stochastic differential equation for the price of the underlying asset that reflects this combined jump and diffusion process is:

$$dS = (\alpha - \lambda k)S\,dt + \sqrt{\nu}S\,dZ + S\,dq \quad \text{(A12)}$$

where, following Merton's[7] notation, α is the instantaneous expected return on the stock, ν is the instantaneous variance of the return conditional on no jumps in stock price occurring, dZ is, as before, a standard Wiener process, $q(t)$ is the independent Poisson process described in (A11), dq and dZ are independent, $\kappa \equiv E[Y-1]$ where $Y-1$ is the random variable percentage change in the stock price if the Poisson event occurs, and E is the expectation operator over the random variable Y.
Merton[7] points out that a closed form solution exists if the random variable Y has a log-normal distribution.
Let the variance of the logarithm of Y equal β^2 and define $\gamma \equiv \log(1+\kappa)$. Define the random variable:

$$X_n \equiv \prod_n Y_n \quad \text{(A13)}$$

with the condition that:

$$X_0 \equiv 1 \quad \text{(A14)}$$

The variable n is the number of Poisson jumps that occur during the life of the option. X_n is distributed lognormally with $E[X_n] = \exp[n\gamma]$ and the variance of the logarithm of X_n equal to $\beta^2 n$. Merton[7] defines:

$$f_n(S,\ T-t) = C(S,\ T-t,\ K,\ \sigma_n^2,\ r_n) \quad \text{(A15)}$$

where

$$\sigma_n^2 \equiv \nu + \frac{n\beta^2}{(T-t)} \quad \text{(A16)}$$

and

$$r_n \equiv r - \lambda\kappa + \frac{n\gamma}{(T-t)} \qquad \text{(A17)}$$

$C(\cdot)$ is the Black–Scholes pricing formula with the five input variables identified in (A15). The option pricing expression that follows from the stochastic specification in (A12), unpriced jump risk, and lognormally distributed random variables Y_n is:

$$F(S,\ T-t) = \sum_{n=0}^{\infty} \frac{e^{-\lambda'(T-t)}(\lambda'(T-t))^n}{n!} f_n(S,\ T-t) \qquad \text{(A18)}$$

where

$$\lambda' \equiv \lambda(1+\kappa) \qquad \text{(A19)}$$

The discrete time version of (A12) is:

$$S(t_{i+1}) = S(t_i)X_n(\Delta t_i)\exp[(\mu - v/2 - \lambda\kappa)\Delta t + (\sqrt{v}x_1\sqrt{\Delta t})] \qquad \text{(A20)}$$

In (A20) $X_n(\Delta t_i)$ is the product of all of the n jumps Y_n that occur within the ith time interval Δt_i. $X_n(\Delta t_i)$ is determined by first determining the number of jumps, n, in the time interval Δt_i based on a random draw from the Poisson distribution with jump intensity parameter $\lambda\Delta t$. The size of each of the n jumps is determined by making n independent random draws from the distribution of Y. If there are no jumps in Δt_i, then $X_n(\Delta t_i) = X_0(\Delta t_i) = 1$, as in (A4). If one jump occurs in Δt_i, $X_n(\Delta t_i) = X_1(\Delta t_i) = Y_1$. If more than one jump occurs in Δt_i, that is $n>1$, $X_n(\Delta t_i)$ is computed according to (A13).

The random variable Y in the version of the jump-diffusion model which leads to the pricing expression in (A18) is distributed lognormally with $E[Y] = 1 + k$, and $VAR[\ln(Y)] = \beta^2$. This is the model that is implemented in the simulations discussed in the body of the paper. In the simulations, draws are made from the distribution of Y by first generating a random variable x_2 where $x_2 \sim N(0, 1)$ and defining:

$$x_2' \equiv \beta x_2 + \ln(1+k) - \frac{\beta^2}{2} \qquad \text{(A21)}$$

Y is defined in the following way:

$$Y \equiv e^{x_2'} \qquad \text{(A22)}$$

The transformations in (A21) and (A22) ensure that $x'_2 \sim N(\ln(1 + k - (\beta^2/2), \beta^2)$ and Y is distributed lognormally with mean $1 + k$.