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Sensitivity comparison of two option pricing models

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Abstract:
In this paper, we study the Black-Scholes' option pricing model and the Heston option pricing model for calculating theoretical call value in European options. We consider the real market data and compare the call premium value for the two models.
Sensitivity analysis is done for both the model at different moneyness options. We compare the Greeks for Black-Scholes' and Heston option pricing models and elucidate them graphically. We use Matlab software for all mathematical computations and graphs.
Keywords – *Black-Scholes' model, Heston model, European call option, Underlying price, Volatility, Interest rate, Greeks and, Sensitivity.*

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I. Introduction

In finance, stock market is one of the fastest growing areas of interest. Every third person today is a trader in his/her own way. Derivatives and stock market has become a first demand of every person nowadays. Options are the derivatives with a specified payoff function that depends on the price of underlying asset. Options are of many types viz. Binomial options, European options, American options e.t.c. European options are considered to be user friendly and easier to trade. This type of option expires only when maturity / expiration approaches. They are also called plain vanilla options.

Options are again divided among Call and Put Option. A call option provides the right to buy but not the obligation to buy an asset at the particular strike price and on the fixed expiration date. Put option provide the right to sell but not the obligation to sell an asset at the particular strike price and on the fixed expiration date. In order to calculate the premium price of option, many scientists working since 60's. Option pricing model was first introduced by Fischer Black and Myron Scholes in 1973. It gives the European call option price of underlying asset. Though it is based on certain assumptions, this model is considered to be the best for option price approximation by traders universally. It is considered as the base model for implied volatility. The option price is calculated in three ways. First, is the intrinsic value i.e. the difference between stock price and strike price. If any option is In-the-money that is, its stock price is greater than strike price, then the trader will get profit by buying a call option or selling a put option at its expiration. And, if option is Out-of-the-money, where strike price is greater than stock price, then the trader will incur a loss by buying a call option and selling a put option at expiration. Second is the time value, if any option is Out-of-the-money in starting then there is a possibility that it comes In-the-money during expiration. It is calculated by the time remaining for expiration. Third and most important is the volatility, it shows how much the stock is volatile or change from its previous position. Higher the volatility, higher is the range of future price. The main drawback of Black-Scholes' model is that it consider volatility as constant quantity.

A stochastic volatility models was introduced in 1993 by Heston. This was named after S. Heston, it calculates the option premium price considering volatility as the stochastic quantity. This also helps in removing excess skewness and kurtosis from the model.

Earlier many researchers studied stochastic volatility model like Wiggins, Hull and White, Stein and Stein, Heston, Bates, Lewis, Bakshi, Chao and Chen. Heston in 1993 gave the theoretical pricing formula for option price. This model is used against the limitations of Black-Scholes' pricing model. It is considered to be much more refined and approximate.

In order to estimate the risk in the option, sensitivity is calculated. Sensitivity is also termed as Greeks. Mathematically, it is the derivative of a dependant variable with respect to an independent parameter. In option pricing model it measure the risk of stock price with respect to different parameters. It is very much helpful to traders and market investors as it describes the nature of the particular parameter in the market fluctuation. There are mainly five types of Greeks calculated in option. They are Delta, Gamma, Theta, Vega and Rho.

- **Delta:** Mathematically, it calculates the first derivative of option price with respect to underlying stock price. Underlying price is the price at which the underlying security is trading on the market at the moment option is priced.

Delta measures the option in price sensitivity relative to the unit change in the underlying stock price. It is important as a risk measure. Traders, especially dealers in options, use delta to construct hedges to offset the risk they have assumed by buying and selling option.

- **Gamma:** It is the numerical measure of how sensitive the delta is to a change in the underlying stock price. When gamma is large the delta changes rapidly and cannot provide a good approximation of how much the option moves for each unit of movement in the underlying price.
- **Theta:** Mathematically, Theta is the first derivative of options price with respect to time to expiration. It measures the sensitivity of the option price to passing time. It calculates the time decay, which is slow for long term options and vice-versa for short term. Also, theta is highest for at-the-money options and lower foe out-of-the-money option.
- **Vega:** It measures sensitivity of the option price to change in volatility. Mathematically, Vega is the first derivative of option price with respect to volatility. It shows the change in option price when implied volatility rises by one percentage point per annum. Vega is positive for long option positions (both call and put), negative for short. Since volatility affects time value, vega varies like time value of an option. It is greatest for at-the-money option and lowest for out-of-the-money.
- **Rho:** The sensitivity of the option price to the risk-free rate is called Rho. It measures the change in premium value for one percentage change in risk-free rate. The higher the interest rate, higher the call premium value. For long term option interest rate affects while for short term option no such change is measured.

Furthermore, there are many Greeks other than the above but in this paper, we only uses the initial five Greeks Delta, Theta, Vega, Gamma and Rho. We compare these values for Black-Scholes model and Heston stochastic model.

This paper is structured as follows; Literature Review, Terminologies, Methodology, Results and Conclusion.

Black-Scholes Model: This model is based on certain assumptions;

- Stock pays no dividends.
- Option can only be exercised upon expiration.
- Random walk.
- No transaction cost.
- Interest rate remains constant.
- Stock returns are normally distributed, thus the volatility is constant over time.

The Black-Scholes Formula for European call price is,

$$C = S_0 N(d_1) - Ke^{-rt} N(d_2)$$

Where, $d_1 = \frac{ln(S_0/K) + (r+\sigma^2/2)t}{\sigma\sqrt{t}}$ and $d_2 = d_1 - \sigma\sqrt{t}$

K is the strike price, S_0 today's stock price, t is time to expiration, r riskless interest rate (constant), σ is volatility of stock (constant).

Heston Model: The price of a European call option can be obtained by using the following equation:

$$C = S_0\Pi_1 - e^{-rt}K\Pi_2$$

Where, Π_1 is the delta of the option and Π_2 is the risk-neutral probability of exercise (i.e. when $S_t > K$)

For j=1, 2 the Heston characteristic function is given as;

$$f_j(x, v, \tau; \emptyset) = e^{C(\tau;\emptyset) + D(\tau;\emptyset)v + i\emptyset x}$$

Where,

$$C(\tau; \emptyset) = r\emptyset i\tau + \frac{a}{\sigma^2}\left\{\left(b_j - \rho\sigma\emptyset i + d\right)\tau - 2ln\left[\frac{1 - ge^{d\tau}}{1 - g}\right]\right\}$$

$$D(\tau; \emptyset) = \frac{b_j - \rho\sigma\emptyset i + d}{\sigma^2}\left[\frac{1 - e^{d\tau}}{1 - ge^{d\tau}}\right]$$

$$g = \frac{b_j - \rho\sigma\emptyset i + d}{b_j - \rho\sigma\emptyset i - d}$$

$$d = \sqrt{\left(\rho\sigma\emptyset i - b_j\right)^2 - \sigma^2\left(2u_j\emptyset i - \emptyset^2\right)}$$

$$u_1 = \frac{1}{2}, u_2 = -\frac{1}{2}, a = k\theta, b_1 = k - \rho\sigma, b_2 = k$$

The characteristic functions can be inverted to get the required probabilities

$$\Pi_j(x, v, T; \ln[K]) = \frac{1}{2} + \frac{1}{\pi}\int_0^{\infty} Re\left[\frac{e^{-i\phi \ln[K]} f_j(x, v, T; \phi)}{i\phi}\right] d\phi$$

Greeks: There are mainly five Greeks discussed in this paper. They are;

- **i.** **Delta:** It measures the change in option price with the change in underlying stock price. It is denoted by $\frac{\partial C}{\partial S}$
- **ii.** **Gamma:** It measures the change in delta with the change in underlying stock price. It is denoted by $\partial^2 C/\partial S^2$
- **iii.** **Theta:** It measures the change in option price with the change in time to expiration. It is denoted by $\frac{\partial C}{\partial t}$
- **iv.** **Vega:** It measures the change in option price with the change in implied volatility. It is denoted by $\frac{\partial C}{\partial \sigma}$
- **v.** **Rho:** It measures the change in option price with the change in interest- free rate. It is denoted by $\frac{\partial C}{\partial r}$

II. Material and Methods

Data: We have collected the call option Historical data for five different companies from the website of National stock Exchange of India. The data of Bank of Baroda, Idea, Punjab National Bank, SAIL and ITC at three different strike prices, they are At-the-money (ATM), It-the-money (ITM) and Out-of-the-money (OTM). We have considered the period from November 2, 2021 to December 31, 2021, where the expiration date is January 27, 2022.

Parameters: The option moneyness is defined as the percentage difference between the current underlying price and the strike price:

Moneyness(%) = S / K-1

The output have been divided in terms of moneyness and time-to-maturity.

ATM - At the money, A call option is at the money if the strike price is the same as the current underlying stock price. Moneyness lies between -2% and 2%

ITM – In the money, A call option is in the money when the strike price is below the underlying stock price. Moneyness lies between 2% and 6%

OTM – Out of the money, A call option is out of the money when the strike price is above the underlying stock price. Moneyness lies between -2% and -6%

I have used Matlab function *bsm_price* and run the model to calculate the European call option value under;

Risk –Free Interest rate: It is the rate at which we deposit or borrow cash over the life of the option. Call option value increases as the risk-free rate increases. It takes value 0.05 throughout the function.

Volatility: It is the standard deviation of the continuously compounded return of the stock. Call option value is higher for higher the volatility. It takes value 0.1, 0.2, 0.3, 0.4, 0.5

I have used Matlab function *heston_chfun* for the Heston characteristic function and *heston_price* for the calculation of European call option value under;

Initial Variance: Bounds of 0 and 1 have been used.

Long-term Variance: Bounds of 0 and 1 have been used.

Correlation: Correlation between the stochastic processes takes values from -1 to 1.

Volatility of variance: It exhibits positive values. Since the volatility of assets may increase in short term, a broad range of 0 to 5 will be used.

Mean-reversion speed: This will be dynamically set using a non-negative constraint (Feller, 1951). The constraint $2k\theta - \sigma^2 > 0$ guarantees that the variance in CIR process is always strictly positive.

Initial variance = 0.28087

Long-term variance = 0.001001

Volatility of variance = 0.1

Correlation Coefficient = 0.5

Mean Reversion Speed = 2.931465

After the calculation of Black-Scholes' and Heston Call price, sensitivity of the Greeks is then calculated for per unit change in stock price, time of expiration, volatility and risk free rate. Thus, the comparison is done graphically in Matlab software.

III. Result

Table -1

Bank of Baroda , K = 120, OTM			
Stock Price (S)	Call Premium (C_1)	Black-Scholes' (B_1)	Heston (H_1)
80.15	0.05	0.009	0
80.95	0.05	0.01	0

81.95	0.1	0.001	0.002
87.05	0.6	0.57	0.008
87.55	0.8	0.71	0.01
88.1	0.8	0.76	0.01
93.15	0.9	0.91	0.05
93.35	1.8	1.92	0.06
94.2	1.2	1.2	0.07
102.3	5.3	5.53	0.51

Table 1: we observe that the price of Black-Scholes' call premium (B_1) and Heston call premium (H_1) are lesser than the actual market call premium (C_1). Here, Out-of-the-money option the price of B_1 is very close to C_1 as compare to H_1. Thus, we can say that in the particular data, Black-Scholes' outcomes Heston model.

Table -2

Bank of Baroda , K = 100, ATM			
Stock Price (S)	Call Premium (C_2)	Black-Scholes' (B_2)	Heston (H_2)
80.15	0.3	0.34	0.08
80.95	0.35	0.4	0.1
81.95	0.3	0.49	0.14
87.05	2.05	3.06	0.57
87.55	3.5	3.46	0.64
88.1	3.6	3.64	0.72
93.15	4.55	4.67	1.88
93.35	6.2	6.6	1.97
94.2	3.5	5.43	2.13
102.3	12.45	12.93	6.67

Table 2: we observe that the price of Black-Scholes' call premium (B_1) are higher and Heston call premium (H_1) are lesser than the actual market call premium (C_1) respectively. Here at-the-money option the price of B_1 is very close to C_1 as compare to H_1. Thus, we can say that in the particular data, Black-Scholes' outcomes Heston model.

Table -3

Bank of Baroda , K = 80, ITM			
Stock Price (S)	Call Premium (C_3)	Black-Scholes' (B_3)	Heston (H_3)
80.15	4.05	4.82	3.63
80.95	4.55	5.27	4.08
81.95	4.61	5.87	4.69
87.05	11.25	11.53	8.86
87.55	11.95	12.15	9.35
88.1	12.25	12.55	9.83
93.15	15.45	15.77	14.26
93.35	16.75	17.33	14.9
94.2	16.5	16.89	15.42
102.3	25.25	26	24.12

Table 3: we observe that the price of Black-Scholes' call premium (B_1) are higher and Heston call premium (H_1) are lesser than the actual market call premium (C_1) respectively. Here In-the-money option the price of H_1 is very close to C_1 as compare to B_1. Thus, we can say that in the particular data, Black-Scholes' outcomes Heston model.

Further, Greeks Delta, Gamma, Theta, Vega and Rho are calculated for per unit change in Stock price, Time, Volatility and Rate respectively. The following observations are explained for the BOB Stock at Out-of-the-money option.

Table 4

Stock Price (S)	Black-Schloes' (B_1)	Heston (H_1)
	Delta	Delta
102.3	-	-
102.31	0.349846	0.100817
102.32	0.349984	0.100976
102.33	0.350121	0.101134
102.34	0.350258	0.101293
102.35	0.350395	0.101452
102.36	0.350533	0.101612
102.37	0.35067	0.101771

102.38	0.350807	0.101931

Table 4, we have considered roughly 10 values of stock price with per unit change. We observe that the as the stock price increases by 1% the Delta value increase by 0.0001 in both Black-Scholes' and Heston model. Thus, we can say that both the models are equally sensitive to stock price.

Table 5

Stock Price (S)	Black-Schloes' (B_1)	Heston (H_1)
	Gamma	Gamma
102.3	-	-
102.31	-	-
102.32	0.013724	0.015854
102.33	0.013725	0.015872
102.34	0.013725	0.015889
102.35	0.013726	0.015906
102.36	0.013727	0.015924
102.37	0.013727	0.015941
102.38	0.013728	0.015959

Table 5, we have considered roughly 10 values of stock price with per unit change. We observe that the as the stock price increases by 1% the Gamma value increase by 0.000001 in both Black-Scholes' and Heston model. Thus, we can say that both the models are equally sensitive to stock price. Gamma is the second derivative than Delta. Therefore, the sensitivity in Gamma is very small as compare to Delta.

Table 6

Time (T)	Black-Schloes' (B_1)	Heston (H_1)
	Theta	Theta
0.23		
0.24	24.60944	0.699466
0.25	24.33794	0.698766
0.26	24.07388	0.698068
0.27	23.8172	0.69737
0.28	23.56777	0.696673
0.29	23.32541	0.695977
0.3	23.08994	0.695281

0.31	22.86115	0.694586

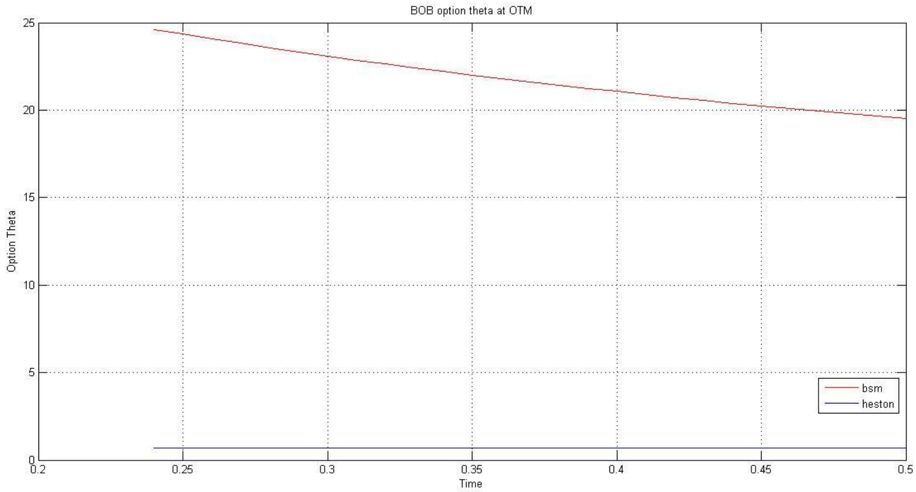

Table 6, we have considered roughly 10 values of Time parameter with per unit change. We observe that the as the time value increases by 1% the theta value decreases by 0.25 approximately in Black-Scholes' and 0.007 in Heston model. Thus, we can say that both the models are sensitive to time. As the time approaches to expiration, the theta value declines. Thus, the sensitivity in Black-Scholes' model is higher as compare to Heston model.

Table 7

Volatility (V)	Black-Schloes' (B_1)	Heston (H_1)
	Vega	Vega
0.55		
0.56	18.20874	0.103541
0.57	18.28716	0.103551
0.58	18.36143	0.103561
0.59	18.43179	0.103571
0.6	18.49847	0.103581
0.61	18.56167	0.103591
0.62	18.6216	0.103601
0.63	18.67844	0.103611

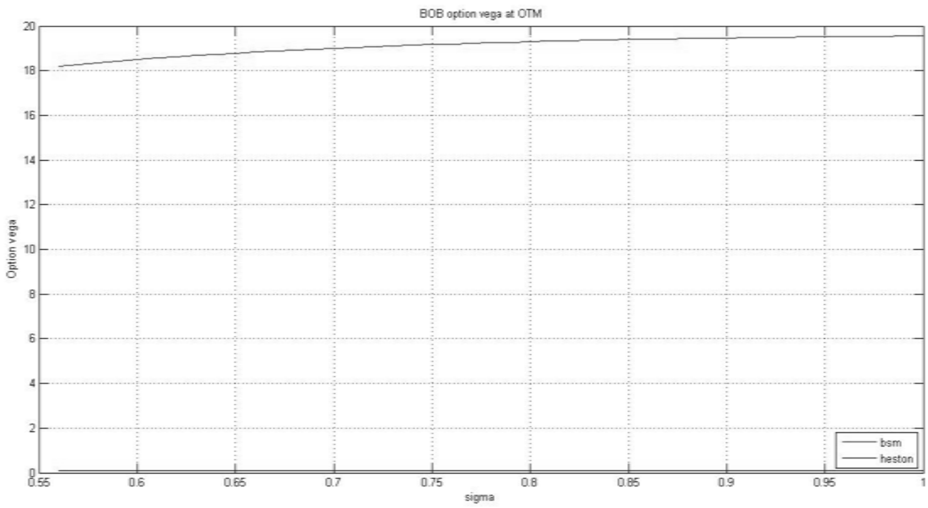

Table 7, we have considered roughly 10 values of volatility parameter with per unit change. We observe that the as the volatility value increases by 1% the vega value increases by 0.08 approximately in Black-Scholes' and 0.00001 in Heston model. Thus, we can say that both the models are sensitive to volatility. As the market becomes more volatile, the vega value increases. Thus, the sensitivity in Black-Scholes' model is higher as compare to Heston model.

Table 8

Rate (R)	Black-Schloes' (B_1)	Heston (H_1)
	Rho	Rho
0.1		
0.11	6.987435	1.607726
0.12	7.047523	1.604032
0.13	7.107721	1.600347
0.14	7.168024	1.59667
0.15	7.228426	1.593002
0.16	7.288922	1.589343
0.17	7.349506	1.585691
0.18	7.410174	1.582048

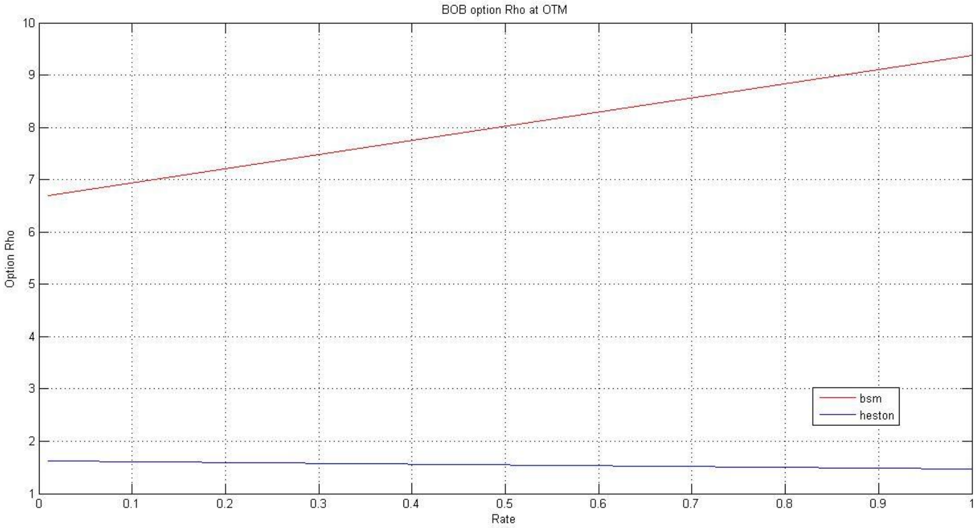

Table 8, we have considered roughly 10 values of rate parameter with per unit change. We observe that the as the rate value increases by 1% the rho value increases by 0.06 approximately in Black-Scholes' and decreases by 0.0037 in Heston model. Thus, we can say that both the models differ from each other. As the rate of interest increases, the demand in the market increases. Thus, the sensitivity in Heston model is greater as compare to Black-Scholes' model.

Likewise, the Greeks are calculated for the stocks of, Idea, Punjab National Bank, SAIL and ITC at three different strike price, Out-of-the-money, At-the-money and In-the-money option. All the results are compared and concluded.

IV. Discussion

As it is discussed in methodology, we have considered five different stocks of Bank of Baroda, Idea, Punjab National Bank, SAIL and ITC at three different strike price, Out-of-the-money, At-the-money and In-the-money option. We have calculated the European call premium for both Black-Scholes' and Heston model for all five stocks.

Further, we have calculated Greeks such as; Delta, Gamma, Theta, Vega and Rho with respect to Black- Scholes' and Heston model at 3 different strikes prices for all the five stocks. The comparison of Greeks is then done graphically using Matlab software.

The following are the observations for five selected stocks.

In Bank of Baroda, at OTM option Black-Scholes' model is more sensitive to the stock price, time and volatility while, Heston model is highly sensitive to rate. At ATM option Black-Scholes' model is more sensitive to time and volatility while, Heston is sensitive to stock price and rate. At ITM option, Black-Scholes' is sensitive to time and volatility while Heston is sensitive to rate.

In Idea, at OTM and ATM option Black-Scholes' is more sensitive to time and volatility while Heston is sensitive to stock price and rate. At ITM option Black-Scholes' is highly sensitive to stock price, time and volatility while Heston is more sensitive to rate.

In Punjab National Bank, at OTM option Black-Scholes' is more sensitive to volatility while Heston is highly sensitive to stock price. At ATM option Black-Scholes' is more sensitive to time and volatility while Heston is sensitive to rate. At ITM option Black-Scholes' is highly sensitive to stock price, time and volatility.

In SAIL, at OTM option Black-Scholes' is more sensitive to stock price, time and volatility while Heston is sensitive to rate. At ATM option black-Scholes' is more sensitive to time and volatility while Heston is sensitive to stock price and rate. At ITM option Black-Scholes' model is more sensitive to time and volatility and Heston to rate.

In ITC, at OTM option Black-Scholes' model is more sensitive to time and volatility while Heston to stock price and rate. At ATM and ITM option Black-Scholes' model is more sensitive to time and volatility while Heston to rate.

V. Conclusion

Thus, we can conclude that among five different stocks, the sensitivity variation is shown higher in Black-Scholes' model for time and volatility, with higher values of Theta and Vega respectively for all the three option of moneyness. Heston model shows the highest sensitivity for rate with higher decreasing value of rho for the three option of moneyness. There is not much variation observed for stock price i.e. Delta and Gamma for any particular model. Both the models had almost equal impact during all the three option of moneyness.

This study shows the actual behaviour of model parameters. It will be helpful in choosing derivatives for long term and short term investments.

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Neha Sisodia. et. al. "Sensitivity comparison of two option pricing models." *IOSR Journal of Mathematics (IOSR-JM)*, 18(6), (2022): pp. 21-29.