ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
Vol. 3, Issue 6 , June 2016

# Elimination-Minimization Principle: Fitting of Exponential Curve to Numerical Data

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**ABSTRACT**: An approach of estimation of parameters had been introduced in 2011 where the usual principle of least squares is applied to each parameter separately. This is done, for each parameter, by obtaining one model, containing the single parameter to be estimated. Later on this approach was termed in 2014 as stepwise least squares method. The principle involved in the approach has in 2015 been termed as elimination-minimization principle. The approach has already been applied successfully in fitting of polynomial curve to numerical data. This paper describes the method of fitting, by the approach, of the two curves namely simple exponential curve and modified exponential curve with numerical example.

**KEYWORDS**: Elimination-minimization principle, exponential curve, fitting to numerical data.

## I. Introduction

The method of least squares is indispensible and is widely used method of curve fitting to numerical data. The method of *Mansfield* (1877*a* , 1877*b*), Stigler (1977 , 1981) et al} and it has been established with the works of the renowned statistician *Adrian* (1808), the German Astronomer *Gauss* {Gauss (1809*a* , 1809*b* , 1929), Hall (1970), Buhler (1981), Sheynin (1979), Sprott (1978), Stigler (1977), et al], the mathematicians viz. *Ivory* (1825), *Hagen* (1837), *Bassel* (1838), *Donkim* (1857), *Herscel* (1850), *Crofton* (1870) etc..

In fitting of a curve by the method of least squares, the parameters of the curve are estimated by solving the normal equations which are obtained by applying the principle of least squares with respect to all the parameters associated to the curve jointly (simultaneously). However, for a curve of higher degree polynomial and / or for a curve having many parameters, the calculation involved in the solution of the normal equations becomes more complicated as the number of normal equations then becomes larger. Moreover, in many situations, it is not possible to obtain normal equations by applying the principle of least squares with respect to all the parameters simultaneously. These lead to think of searching for some other approach of estimation of parameters. For this reason, an approach of estimation of parameters had been introduced (Dhritikesh, 2011) where the usual principle of least squares is applied to each parameter separately. This is done, for each parameter, by obtaining one model, containing the single parameter to be estimated. Later on, this approach was termed as stepwise least squares method (Dhritikesh, 2014). The principle involved in the approach has been termed in 2015 as elimination-minimization principle (Atwar & Dhritikesh, 2015*a*). The approach has already been applied successfully in fitting of polynomial curve to numerical data {Atwar & Dhritikesh (2015*a* , 2015*b* , 2015*c* , 2015*d*), Dhritikesh (2016)}. In the current study, the approach has been applied in the fitting of simple exponential curve and modified exponential curve to numerical data. This paper describes the method of fitting of the two curves, by the approach, with numerical example.

## II. FITTING OF EXPONENTIAL CURVE

Hence forward, one operator namely Δ is used with the following definition:

$$\Delta Y_i = Y_{i+1} - Y_i$$

$$\& \ \Delta X_i = X_{i+1} - X_i$$

$$(\text{for } i = 1 , 2 , 3 , \ldots\ldots\ldots\ldots ).$$

Let a variable $Y$ be dependent on another variable $X$ and the exponential function satisfied by them be of the form

$$Y = \alpha .exp ( \beta X) \qquad (2.1)$$

Taking logarithm on both sides of (2.1) one can have

$$\log_e Y = \text{Log}_e \alpha + \beta X$$

ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
Vol. 3, Issue 6 , June 2016

i.e. $$Z = \eta + \beta X \tag{2.2}$$

where $Z = \text{Log}_e Y$ & $\eta = \text{Log}_e \alpha$

Thus the logarithm of $Y$ is a linear function of $X$.

Now, let

$$Y_1, Y_2, Y_3, \ldots\ldots\ldots\ldots, Y_n$$

be the observed values assumed by the dependent variable $Y$ corresponding to the values

$$X_1, X_2, X_3, \ldots\ldots\ldots\ldots, X_n$$

of the independent variable $X$ ,

**First, let us consider the situation where the observations perfectly follow the exponential low described by equation (2.1).**

In this situation,

$$Y_i = \alpha .exp(\beta X_i) \quad , (i = 1, 2, \ldots\ldots\ldots, n) \tag{2.3}$$

Accordingly,

$$\log_e Y_i = \log_e \alpha + \beta X_i \quad , (i = 1, 2, \ldots\ldots\ldots, n)$$

$$\text{i.e. } Z_i = \eta + \beta X_i \quad , \tag{2.4}$$

where $Z_i = \log_e Y_i$ , $(i = 1, 2, \ldots\ldots\ldots, n)$ .

Applying the operator $\Delta$ on both sides of equation (2.4), it is obtained that

$$\Delta Z_i = \beta . \Delta X_i$$

$$\text{i.e. } \beta = (\Delta Z_i) / (\Delta X_i) \ , \ (i = 1, 2, \ldots\ldots\ldots, n-1) \tag{2.5}$$

Since the observed values perfectly follow the exponential law, all the values of

$$(\Delta Z_i) / (\Delta X_i) \ , \ (i = 1, 2, \ldots\ldots\ldots, n-1)$$

are equal and the common value is the value of the parameter $\beta$ .

Substituting this value of $\beta$ in equations (2.4), one obtains $(n-1)$ equations in $\eta$. Solving any one of these equations, the value of $\eta$ can be obtained and then taking the antilogarithm of it the value of $\alpha$ can be obtained.

**Now, let us consider the situation where the observations do not perfectly follow the exponential low described by equation (2.1)**

It may be the situation that the observed values may not perfectly follow the exponential law described by equation (2.1) and the observations may suffer from error.

In the situation, where either or both of the two possibilities do influence, the observed values will follow the model

$$Y_i = \alpha .exp(\beta X_i). e_i \quad , (i = 1, 2, \ldots\ldots\ldots, n) \tag{2.6}$$

where $e_i$ is the error/error associated to $Y_i$ as multiplicative factor.

This implies,

$$Z_i = \eta + \beta X_i + \varepsilon_i \quad , \quad (i = 1, 2, \ldots\ldots\ldots, n) \tag{2.7}$$

where $Z_i = \log_e Y_i$ and $\varepsilon_i$ is the error/deviation associated to $Z_i$ .

In order to apply the elimination-minimization principle (Atwar & Dhritikesh, 2015*a*), the parameter $\eta$ is to be eliminated first.

Operating on both sides of equation (2.7) one can have

$$\Delta Z_i = \beta . \Delta X_i + \Delta \varepsilon_i \quad , \ (i = 1, 2, \ldots\ldots\ldots, n-1) \tag{2.8}$$

Minimizing the sum of squares of $\Delta \varepsilon_i$ $(i = 1, 2, \ldots\ldots\ldots, n-1)$ with respect to $\beta$ , its estimator is found as

$$\hat{\beta}_{(EM)} = \frac{1}{h(n-1)} \sum_{i=1}^{n-1} \Delta Z_i \tag{2.9}$$

Substituting the estimator of $\beta$ in equation (2.7) and then applying similar minimization method the estimator of $\eta$ is found to be

$$\hat{\eta}_{(EM)} = \bar{Z} - \hat{\beta}_{(EM)} \bar{X} \tag{2.10}$$

which yields the estimate of $\alpha$ as

ISSN: 2350-0328

International Journal of Advanced Research in Science, Engineering and Technology

Vol. 3, Issue 6 , June 2016

$$\left.\begin{aligned} &\widehat{\alpha}_{(EM)} = anti\log_e(\widehat{\eta}_{(EM)}) \\ \text{i.e.}\quad &\widehat{\alpha}_{(EM)} = anti\log_e(\overline{Z} - \widehat{\beta}_{(EM)}) \end{aligned}\right\} \qquad (2.11)$$

## III. FITTING OF MODIFIED EXPONENTIAL CURVE

The modified exponential function $Y = f(X)$ is of the form

$$Y = \mu + \alpha .exp(\beta X) \qquad (3.1)$$

where $\mu$, $\alpha$ and $\beta$ are the three parameters.

As earlier, let

$$Y_1 , Y_2 , Y_3 , \ldots\ldots\ldots\ldots\ldots , Y_n$$

be the observed values assumed by the dependent variable $Y$ corresponding to the values

$$X_1 , X_2 , X_3 , \ldots\ldots\ldots\ldots\ldots , X_n$$

of the independent variable $X$.

**First, let us consider the situation where the observations perfectly follow the modified exponential low described by equation (3.1)**

In this situation,

$$Y_i = \mu + \alpha . exp(\beta X_i) \quad , \quad (i = 1 , 2 , \ldots\ldots\ldots , n) \qquad (3.2)$$

which implies

$$\Delta Y_i = \alpha\ \Delta\ exp(\beta X_i)$$

$$= [exp\{(\beta . (X_i + h)\} - exp(\beta X_i)]$$

$$\text{i.e.}\quad \Delta Y_i = \alpha . exp(\beta X_i)\{exp(\beta h) - 1\}$$

$$\text{i.e.}\quad Z_i = A . exp(\beta X_i) \quad , \quad (i = 1 , 2 , \ldots\ldots\ldots , n-1) \qquad (3.3)$$

where $Z_i = \Delta Y_i$ , $A = \alpha . \{exp(\beta h) - 1\}$ & $h$ is the interval of the values of $X$.

Taking logarithm of both side of (3.3),

$$\log Z_i = \log A + \beta . X_i$$

$$\text{i.e.}\quad Z_i' = A' + \beta X_i \quad , \quad (i = 1 , 2 , \ldots\ldots\ldots , n-1) \qquad (3.4)$$

where $Z_i' = \log Z_i$ and $A' = \log A$.

From (3.4) ,

$$\Delta Z_i' = \beta . \Delta X_i$$

$$\text{i.e.}\quad \beta = (\Delta Z_i') / (\Delta X_i) \ , \quad (i = 1 , 2 , \ldots\ldots\ldots , n-2) \qquad (3.5)$$

Since the observed values perfectly follow the modified exponential law, all the values of

$$(\Delta Z_i') / (\Delta X_i) \quad , \quad (i = 1 , 2 , \ldots\ldots\ldots , n-2)$$

are equal and the common value is the value of the parameter $\beta$ .

Substituting this value of $\beta$ in (3.4) one obtains $(n-1)$ equations in $A' = \log A$.

Solving any one of these equations, the value of $A' = \log A$ can be found out and then taking the antilogarithm of it the value of $A$ can be obtained.

Consequently, $\alpha$ can be obtained from

$$A = \alpha . \{exp(\beta h) - 1\} \qquad (3.6)$$

Finally, the parameter $\mu$ can be obtained from any one of the equations (3.2).

**Now, let us consider the situation where the observations do not perfectly follow the modified exponential low described by equation (3.1)**

It may be the situation that the observed values may not perfectly follow the exponential law described by equation (3.1) and the observations may suffer from error.

ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
Vol. 3, Issue 6 , June 2016

In the situation, where either or both of the two possibilities do influence, the observed values will follow the model

$$Y_i = \mu + \alpha \,.\, exp\,(\beta X_i)\, \delta_i \;,\; (i = 1, 2, \ldots\ldots\ldots, n) \tag{3.7}$$

where $\delta_i$ is the error associated to $Y_i$ .
This implies,

$$Z_i = A \,.\, exp\,(\beta X_i) \times \varepsilon_i^{\prime} \;,\quad (i = 1, 2, \ldots\ldots\ldots, n-1) \tag{3.8}$$

where $\varepsilon_i^{\prime}$ is the error associated to $Z_i$ .
Taking logarithm of both side of (3.8)

$$\log Z_i = \log A + \beta . X_i + \epsilon_i$$

$$\text{i.e. } Z_i^{\prime} = A^{\prime} + \beta X_i + \epsilon_i \;,\; (i = 1, 2, \ldots\ldots\ldots, n-2) \tag{3.9}$$

where $Z_i^{\prime} = \log Z_i$ , $A^{\prime} = \log A$ & $\epsilon_I = \log \varepsilon_i^{\prime}$.
From (3.9)

$$\Delta Z_i^{\prime} = \beta \,.\, \Delta X_i + \Delta \epsilon_i \;,\; (i = 1, 2, \ldots\ldots\ldots, n-2) \tag{3.10}$$

Applying the elimination-minimization principle the estimate of the parameters $\beta$ and $A^{\prime}$ can be obtained as

$$\widehat{\beta}_{(EM)} = \frac{1}{h(n-2)} \sum_{i=1}^{n-2} \Delta Z_i^{\prime} \tag{3.11}$$

$$\& \quad \widehat{A}^{\prime} = \overline{Z}^{\prime} - \widehat{\beta}_{(EM)} \overline{X} \tag{3.12}$$

Accordingly, $A = \text{antilog}\,(\widehat{A}^{\prime})$

$$\text{i.e. } A = anti\log(\overline{Z}^{\prime} - \widehat{\beta}_{(EM)} \overline{X}) \tag{3.13}$$

Consequently, estimate of $\alpha$ is obtained as

$$\widehat{\alpha}_{(EM)} = \frac{A}{(e^{\widehat{\beta}_{(EM)}.h} - 1)}$$

$$\text{i.e. } \widehat{\alpha}_{(EM)} = \frac{anti\log(\overline{Z}^{\prime} - \widehat{\beta}_{(EM)} \overline{X})}{(e^{\widehat{\beta}_{(EM)}.h} - 1)} \tag{3.14}$$

Finally from the equations (3.7), one can obtain the estimates of the parameter $\mu$ as

$$\widehat{\mu}_{(EM)} = \overline{Y} - \frac{\widehat{\alpha}_{(EM)}}{n} \sum_{i=1}^{n} e^{\widehat{\beta}_{(EM)}.X_i} \tag{3.15}$$

## IV. NUMERICAL APPLICATION

The method described here has been applied to estimate the total population of India from the data on total population of India (collected for the years from 1951 to 2001 from the census report published by the Registrar General of India) as shown in the following table.

**Table-4.1**
(Observed Total Population of India)

| Year | 1951 | 1961 | 1971 | 1981 | 1991 | 2001 |
|---|---|---|---|---|---|---|
| Total Population | 361088090 | 439234771 | 548159652 | 683329097 | 846302688 | 1027015247 |

First, the exponential curve, described by equation (2.1) has been fitted to these data by the method explained in section II.
The estimated total population of India obtained from the fitted exponential curve, fitted by this method, has been Shown In **Table-4.2**.
The exponential curve, described by equation (2.1) has also been fitted to these data by the usual least squares method

ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
Vol. 3, Issue 6 , June 2016

(i.e. estimation by solving normal equations). explained in section II. The estimated total population of India obtained From the fitted exponential curve, fitted by this method, has been shown in the same table i.e. in **Table-4.2**.

**Table-4.2**
(Estimated Population of India by Exponential curve)

| (1) | (2) | (3) | (4) |
|---|---|---|---|
| Year | Observed Total Population | Estimated Total Population (by the method explained in section II) | Estimated Total Population (by usual least squares method) |
| 1951 | 361088090 | 361834305 | 359327530 |
| 1961 | 439234771 | 445966754 | 444110392 |
| 1971 | 548159652 | 549661386 | 548897660 |
| 1981 | 683329097 | 677466732 | 678409347 |
| 1991 | 846302688 | 834988930 | 838479147 |
| 2001 | 1027015247 | 1029137639 | 1036317209 |

Next, the modified exponential curve, described by equation (3.1) has been fitted to these data by the method explained In section III. The estimated total population of India obtained from the fitted exponential curve, fitted by this method, Has been shown in **Table-4.3**.

The modified exponential curve, described by equation (2.1) has also been fitted to these data by the usual least squares method (i.e. estimation by solving normal equations). The estimated total population of India obtained from the fitted modified exponential curve, fitted by this method, has been shown in the same table i.e. in **Table-4.3**.

**Table-4.3**
(Estimated Population of India by Modified Exponential curve)

| (1) | (2) | (3) | (4) |
|---|---|---|---|
| Year | Observed Total Population | Estimated Total Population (by the method explained in section III) | Estimated Total Population (by usual least squares method) |
| 1951 | 361088090 | 391867773 | 363105958 |
| 1961 | 439234771 | 467456272 | 447318193 |
| 1971 | 548159652 | 560668989 | 550996946 |
| 1981 | 683329097 | 675615189 | 678642105 |
| 1991 | 846302688 | 817362253 | 835793747 |
| 2001 | 1027015247 | 992159070 | 1029272599 |

## V. CONCLUSION

(1) The elimination-minimization approach has already been found suitable for finding of method of fitting of a
(2) In this study, the approach has been found suitable for finding of method of fitting of exponential types of curves to numerical data.
(3) It is yet to be investigated whether this approach can be applicable in finding of suitable method of fitting of other types of curves to numerical data.
(4) It is yet to be search for whether the estimates of parameter obtained by this method and those obtained by usual method of least squares are identical.

ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
Vol. 3, Issue 6 , June 2016

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ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
Vol. 3, Issue 6 , June 2016

# Author's Biography

ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
Vol. 3, Issue 6 , June 2016

ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
Vol. 3, Issue 6 , June 2016

Dr. Dhritikesh Chakrabarty passed B.Sc. (with Honours in Statistics) Examination from Gauhati University in 1981 securing 1st class &1st position. He passed M.Sc. Examination (in Statistics) from the same university in the year 1983 securing 1st class & 1st position and successively passed M.Sc. Examination (in Mathematics) from the same university in 1987 securing 1st class (5th position). He obtained the degree of Ph.D. (in Statistics) in the year 1993 from Gauhati University. Later on, he obtained the degree of Sangeet Visharad (inVocal Music) in the year 2000 from Bhatkhande Sangeet vidyapith securing 1st class, the degree of Sangeet Visharad (in Tabla) from Pracheen Kala Kendra in 2010 securing 2nd class, the degree of Sangeet Pravakar (in Tabla) from Prayag Sangeet Samiti in 2012 securing 1st class and the degree of Sangeet Bhaskar (in Tabla) from Pracheen Kala Kendra in 2014 securing 1st class. He obtained Jawaharlal Nehru Award for securing 1st position in Degree Examination in the year 1981. He also obtained Academic Gold Medal of Gauhati University and Prof. V. D. Thawani Academic Award for securing 1st position in Post Graduate Examination in the year 1983.

Dr. Dhritikesh Chakrabarty is also an awardee of the Post Doctoral Research Award by the University Grants Commission for the period 2002─05.

He attended five of orientation/refresher course held in Gauhati University, Indian Statistical Institute, University of Calicut and Cochin University of Science & Technology sponsored/organized by University Grants Commission/Indian Academy of Science. He also attended/participated eleven workshops/training programmes of different fields at various institutes.

Dr. Dhritikesh Chakrabarty joined the Department of Statistics of Handique Girls' College, Guwahati, as a Lecturer on December 09, 1987 and has been serving the institution continuously since then. Currently he is in the position of Associate Professor (& Ex Head) of the same Department of the same College. He has also been serving the National Institute of Pharmaceutical Education & Research (NIPER), Guwahati, as a Guest Faculty continuously from May 02, 2010. Moreover, he is a Research Guide (Ph.D. Guide) in the Department of Statistics of Gauhati University with effect from 31-08-2010 and also Research Guide (Ph.D. Guide) in the Department of Statistics of Assam Down Town University with effect from 29-01-2013. He has been guiding a number of Ph.D. students in the two universities. He acted as Guest Faculty in the Department of Statistics and also in the Department of Physics of Gauhati University. In the mean time, he guided some M. Phil. Students of Vinayak Mission University. He also acted as Guest Faculty cum Resource Person in the Ph.D. Course work Programme in the Department of Computer Science and also in the Department of Biotechnology of the same University for the last six years. Dr. Chakrabarty has been working as an independent researcher for the last more than twenty five years. He has already published sixty eight research papers in various research journals mostly of international level and eight research papers in conference proceedings. Fifty four research papers based on his research works have already been presented in research conferences/seminars of national and international levels both within and outside India. He has written a book titled "Statistics for Beginners". He is also one author of the Assamese Science Dictionary titled "Vigyan Jeuti" published by Assam Science Society. Moreover, he is one author of the research book "BIODIVERSITY- Threats and Conservation (ISBN-978-93-81563-48-9)" published by the Global Publishing House. He delivered invited talks/lectures in several seminars He acted as chair person in some seminars. He visited U.S.A. in 2007, Canada in 2011 and U.K. in 2014. He has already completed one post doctoral research project (2002─05) and one minor research project (2010─11). He is an active life member of each of the following academic cum research organizations:

(1) Assam Science Society (ASS)
(2) Assam Statistical Review (ASR)
(3) Indian Statistical Association (IAS)
(4) Indian Society for Probability & Statistics (ISPS)
(5) Forum for Interdisciplinary Mathematics (FIM)
(6) Electronics Scientists & Engineers Society (ESES)
(7) International Association of Engineers (IAENG)

Moreover, he is a Referee of the Journal of Assam Science Society (JASS) and a Member of the Editorial Board of the Journal of Environmental Science, Computer Science and Engineering & Technology (JECET).

Dr. Chakrabarty acted as members (at various capacities) of the organizing committees of a number of conferences/seminars already held.