

# Regression Analysis

Last Updated:

October 11, 2023

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# Chapter 1

## Introduction

The primary goal in regression is to develop a model that relates a set of explanatory variables  $X_1, \dots, X_p$  to a response variable  $Y$ , then test the model and use it for inference and prediction.

Given a set of  $n$  pairs of data  $Y_i$  and  $X_i$ , we attempt to fit a straight line to these points, using a simple regression model

$$Y_i = \beta_0 + \beta_1 X_i + \epsilon_i$$

Where  $\epsilon_i$  represents an unobserved random error term,  $\beta_0$  is the intercept and  $\beta_1$  is the slope of the line.  $\beta_0$  and  $\beta_1$  are parameters that need to be estimated from observed data. The model can also be expressed in terms of  $(X_i - \bar{X})$ .

$$Y_i = (\beta_0 + \beta_1 \bar{X}) + \beta_1 (X_i - \bar{X}) + \epsilon_i$$

Where  $\bar{X}$  is the sample mean

$$\bar{X} = \frac{1}{n} \sum_{i=1}^n X_i$$

This proposed model is linear in the parameters  $\beta_0$ ,  $\beta_1$ , and would still be referred to as linear if we had  $X_i^2$  instead of  $X_i$ . This model also makes the assumption that the random error terms  $\epsilon_i$  are uncorrelated, have mean 0, and variance  $\sigma^2$ . Under these assumptions, we have

$$E(Y_i) = \beta_0 + \beta_1 X_i$$

$$\text{Var}(Y_i) = \sigma^2$$

## Chapter 2

# Simple Linear Regression

The primary goal in regression is to develop a model that relates a set of explanatory variables  $X_1, \dots, X_p$  to a response variable  $Y$ , then test the model and use it for inference and prediction.

Given a set of  $n$  pairs of data  $Y_i$  and  $X_i$ , we attempt to fit a straight line to these points, using a simple regression model

$$Y_i = \beta_0 + \beta_1 X_i + \epsilon_i$$

Where  $\epsilon_i$  represents an unobserved random error term,  $\beta_0$  is the intercept and  $\beta_1$  is the slope of the line.  $\beta_0$  and  $\beta_1$  are parameters that need to be estimated from observed data. The model can also be expressed in terms of  $(X_i - \bar{X})$ .

$$Y_i = (\beta_0 + \beta_1 \bar{X}) + \beta_1 (X_i - \bar{X}) + \epsilon_i$$

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This proposed model is linear in the parameters  $\beta_0$ ,  $\beta_1$ , and would still be referred to as linear if we had  $X_i^2$  instead of  $X_i$ . This model also makes the assumption that the random error terms  $\epsilon_i$  are uncorrelated, have mean 0, and variance  $\sigma^2$ . Under these assumptions, we have

$$E(Y_i) = \beta_0 + \beta_1 X_i$$

$$\text{Var}(Y_i) = \text{Var}(\beta_0 + \beta_1 X_i + \epsilon_i) = \sigma^2$$

Thus the mean of  $Y$  is a linear function of  $X$  however the variance of  $Y$  does not depend on a value of  $X$ .

The parameters  $\beta_0$  and  $\beta_1$  are called the regression coefficients. The slope  $\beta_1$  is the change in the mean of the distribution of  $Y$  produced by a unit change

in  $Y$ . If the range of data on  $X$  includes  $x = 0$ , then the intercept  $\beta_0$  is the mean of the distribution of the response  $Y$  when  $x = 0$ . If the range of  $x$  does not include zero, then  $\beta_0$  has no practical interpretation.

## 2.1 Estimating the Parameters with the Method of Least Squares

The parameters  $\beta_0, \beta_1$  are unknown and must be estimated from the data. Suppose we have  $n$  pairs of data  $(x_1, y_1), (x_2, y_2), \dots, (x_n, y_n)$ .

### 2.1.1 Estimation of $\beta_0$ and $\beta_1$

The method of least squares is the most popular approach to fitting a regression model. Let  $Q$  be the sum of the error terms squared

$$Q = \sum_{i=1}^n \epsilon_i^2 = \sum_{i=1}^n (Y_i - \beta_0 - \beta_1 X_i)^2$$

Then we want to minimize  $Q$  with respect to the parameters  $\beta_1, \beta_2$ ,

$$\frac{\partial Q}{\partial \beta_0} = -2 \sum_{i=1}^n (Y_i - \beta_0 - \beta_1 X_i) = 0$$

$$\frac{\partial Q}{\partial \beta_1} = -2 \sum_{i=1}^n (Y_i - \beta_0 - \beta_1 X_i) X_i = 0$$

We can rearrange these equations to get the following equations

$$\begin{aligned} & -2 \sum_{i=1}^n (Y_i - \beta_0 - \beta_1 X_i) = 0 \\ \implies & \sum_{i=1}^n Y_i - \sum_{i=1}^n \beta_0 - \sum_{i=1}^n \beta_1 X_i = 0 \\ \implies & \sum_{i=1}^n Y_i = n\beta_0 - \beta_1 \sum_{i=1}^n X_i \\ & -2 \sum_{i=1}^n (Y_i - \beta_0 - \beta_1 X_i) X_i = 0 \\ \implies & \sum_{i=1}^n Y_i X_i - \sum_{i=1}^n \beta_0 X_i - \sum_{i=1}^n \beta_1 X_i^2 = 0 \\ \implies & \sum_{i=1}^n Y_i X_i = \beta_0 \sum_{i=1}^n X_i - \beta_1 \sum_{i=1}^n X_i^2 \end{aligned}$$

These 2 equations are known as the normal equations and the solutions to them, call them  $b_0$ ,  $b_1$ , are

$$b_0 = \bar{Y} - b_1 \bar{X}$$

$$b_1 = \frac{\sum_{i=1}^n (X_i - \bar{X})(Y_i - \bar{Y})}{\sum_{i=1}^n (X_i - \bar{X})^2} = \frac{\sum_{i=1}^n (X_i - \bar{X})Y_i}{\sum_{i=1}^n (X_i - \bar{X})^2} = \sum_{i=1}^n k_i Y_i$$

with

$$k_i = \frac{X_i - \bar{X}}{\sum_{i=1}^n (X_i - \bar{X})^2}$$

We also sometimes use a more compact notation, by denoting the corrected sum of squares for  $X$  and the sum of cross products of  $X_i$   $Y_i$  as

$$S_{xx} = \sum_{i=1}^n x_i^2 - \frac{1}{n} \left( \sum_{i=1}^n x_i \right)^2 = \sum_{i=1}^n (x_i - \bar{x})^2$$

$$S_{xy} = \sum_{i=1}^n x_i y_i - \frac{1}{n} \left( \sum_{i=1}^n x_i \right) \left( \sum_{i=1}^n y_i \right) = \sum_{i=1}^n y_i (x_i - \bar{x})$$

So, we can write

$$b_1 = \frac{S_{xy}}{S_{xx}}$$

The observed difference between  $Y_i$  and the corresponding fitted value  $\hat{Y}_i$  is a residual. The  $i$ th residual is

$$e_i = y_i - \hat{y}_i = y_i - (b_0 + b_1 x_i)$$

Note that  $k_i$  has important properties, such as

$$\sum_{i=1}^n k_i = 0, \quad \sum_{i=1}^n k_i X_i = 1, \quad \sum_{i=1}^n k_i^2 = \frac{1}{\sum_{i=1}^n (X_i - \bar{X})^2}$$

$$\begin{aligned} \sum_{i=1}^n k_i &= \frac{\sum_{i=1}^n (X_i - \bar{X})}{\sum_{i=1}^n (X_i - \bar{X})^2} \\ &= \frac{n\bar{X} - n\bar{X}}{\sum_{i=1}^n (X_i - \bar{X})^2} = 0 \end{aligned}$$

$$\begin{aligned}
\sum_{i=1}^n k_i X_i &= \frac{\sum_{i=1}^n (X_i - \bar{X}) X_i}{\sum_{i=1}^n (X_i - \bar{X})^2} \\
&= \frac{\sum_{i=1}^n (X_i^2 - X_i \bar{X})}{\sum_{i=1}^n (X_i - \bar{X})^2} \\
&= \frac{\sum_{i=1}^n X_i^2 - \bar{X} \sum_{i=1}^n X_i}{\sum_{i=1}^n (X_i - \bar{X})^2} \\
&= \frac{\sum_{i=1}^n X_i^2 - n \bar{X}^2}{\sum_{i=1}^n (X_i^2 - 2X_i \bar{X} + \bar{X}^2)} \\
&= \frac{\sum_{i=1}^n X_i^2 - n \bar{X}^2}{\sum_{i=1}^n X_i^2 - 2n \bar{X}^2 + n \bar{X}^2} = 1
\end{aligned}$$

$$\begin{aligned}
\sum_{i=1}^n k_i^2 &= \sum_{i=1}^n \left( \frac{X_i - \bar{X}}{\sum_{i=1}^n (X_i - \bar{X})^2} \right)^2 \\
&= \frac{\sum_{i=1}^n (X_i - \bar{X})^2}{\sum_{i=1}^n (X_i - \bar{X})^4} \\
&= \frac{1}{\sum_{i=1}^n (X_i - \bar{X})^2}
\end{aligned}$$

The equation for the fitted line is then

$$\hat{Y} = b_0 + b_1 X$$

Or alternatively using  $X - \bar{X}$ ,

$$\hat{Y} = (b_0 + b_1 \bar{X}) + b_1 (X - \bar{X})$$

**Theorem 2.1.1** (Gauss Markov Theorem). *The least square estimators  $b_0$ ,  $b_1$  are unbiased and have minimum variance among all unbiased linear estimators.*

*Proof.* Consider an unbiased linear estimator

$$\hat{\beta}_1 = \sum_{i=1}^n c_i Y_i$$



$\hat{\beta}_1$  must satisfy  $E(\hat{\beta}_1) = \beta_1$ .

$$\begin{aligned}
\beta_1 &= E(\hat{\beta}_1) \\
&= E\left(\sum_{i=1}^n c_i Y_i\right) \\
&= \sum_{i=1}^n c_i E(Y_i) \\
&= \sum_{i=1}^n c_i (\beta_0 + \beta_1 X_i) \\
&= \beta_0 \sum_{i=1}^n c_i + \beta_1 \sum_{i=1}^n c_i X_i
\end{aligned}$$

Therefore,  $\sum_{i=1}^n c_i = 0$ , and  $\sum_{i=1}^n c_i X_i = 1$ . We can also see that the variance is

$$\text{Var}(\hat{\beta}_1) = \sum_{i=1}^n c_i^2 \text{Var}(Y_i) = \sigma^2 \sum_{i=1}^n c_i^2$$

Now, set  $c_i = k_i + d_i$  where  $k_i$  is as defined previously above and  $d_i$  are arbitrary constants. We want to show that the variance is minimized, so

$$\begin{aligned}
\text{Var}(\hat{\beta}_1) &= \sum_{i=1}^n c_i^2 \text{Var}(Y_i) \\
&= \sigma^2 \sum_{i=1}^n c_i^2 \\
&= \sigma^2 \sum_{i=1}^n (k_i + d_i)^2 \\
&= \sigma^2 \left( \sum_{i=1}^n k_i^2 + 2 \sum_{i=1}^n k_i d_i + \sum_{i=1}^n d_i^2 \right)
\end{aligned}$$

Note that the variance of  $b_1$  is

$$\text{Var}(b_1) = \text{Var}\left(\sum_{i=1}^n k_i Y_i\right) = \sigma^2 \sum_{i=1}^n k_i^2 = \sigma^2 \frac{1}{\sum_{i=1}^n (X_i - \bar{X})^2}$$

Now notice that there is a relationship between the variance of  $\hat{\beta}_1$  and  $b_1$ , namely that the variance of  $\hat{\beta}_1$  is the same as  $b_1$  plus an additional constants but these

constants are indeed 0.

$$\begin{aligned}
\sum_{i=1}^n k_i d_i &= \sum_{i=1}^n k_i (c_i - k_i) \\
&= \sum_{i=1}^n k_i c_i - \sum_{i=1}^n k_i^2 \\
&= \sum_{i=1}^n c_i \frac{X_i - \bar{X}}{\sum_{i=1}^n (X_i - \bar{X})^2} - \frac{1}{\sum_{i=1}^n (X_i - \bar{X})^2} \\
&= \frac{\sum_{i=1}^n c_i X_i - \sum_{i=1}^n c_i \bar{X}}{\sum_{i=1}^n (X_i - \bar{X})^2} - \frac{1}{\sum_{i=1}^n (X_i - \bar{X})^2}
\end{aligned}$$

We know that  $\sum_{i=1}^n c_i = 0$  and  $\sum_{i=1}^n c_i X_i = 1$ , so this becomes

$$\sum_{i=1}^n k_i d_i = \frac{1 - 0}{\sum_{i=1}^n (X_i - \bar{X})^2} - \frac{1}{\sum_{i=1}^n (X_i - \bar{X})^2} = 0$$

Therefore,

$$\text{Var}(\hat{\beta}_1) = \sigma^2 \left( \sum_{i=1}^n k_i^2 + \sum_{i=1}^n d_i^2 \right)$$

Clearly the variance is minimized when  $d_i = 0$  for all  $i$ , thus

$$\text{Var}(\hat{\beta}_1) = \sigma^2 \sum_{i=1}^n k_i^2 = \text{Var}(b_1)$$

Thus the least squares estimator  $b_1$  has minimum variance along all unbiased estimators.  $\square$

We may write

$$\hat{Y} = b_0 + b_1 X$$

for the estimated or fitted line, and

$$e_i = Y_i - \hat{Y}_i$$

for the estimated  $i^{th}$  residual. The estimate for the variance  $\sigma^2$  is then

$$\hat{\sigma}^2 = \frac{\sum_{i=1}^n e_i^2}{n - 2}$$

The estimate of the variance  $\sigma^2$  is also known as the mean square error (MSE).

### 2.1.2 Properties of Fitted Regression Line

- (i)  $\sum_{i=1}^n e_i = 0$ . Recall that  $\hat{Y} = b_0 + b_1 X = (b_0 + b_1 \bar{X}) + b_1 (X - \bar{X})$ , and

$$\bar{Y} = b_0 + b_1 \bar{X}$$

So  $\hat{Y} = \bar{Y} + b_1 (X - \bar{X})$ , then

$$\begin{aligned} \sum_{i=1}^n e_i &= \sum_{i=1}^n (Y_i - \hat{Y}_i) \\ &= \sum_{i=1}^n Y_i - \sum_{i=1}^n \hat{Y}_i \\ &= \sum_{i=1}^n Y_i - \sum_{i=1}^n (\bar{Y} + b_1 (X_i - \bar{X})) \\ &= n\bar{Y} - n\bar{Y} + b_1 \sum_{i=1}^n (X_i - \bar{X}) \\ &= n\bar{Y} - n\bar{Y} + b_1 (n\bar{X} - n\bar{X}) = 0 \end{aligned}$$

- (ii)  $\sum_{i=1}^n Y_i = \sum_{i=1}^n \hat{Y}_i$ . This follows from the previous property since

$$\sum_{i=1}^n e_i = \sum_{i=1}^n Y_i - \sum_{i=1}^n \hat{Y}_i = 0 \implies \sum_{i=1}^n Y_i = \sum_{i=1}^n \hat{Y}_i$$

- (iii)  $\sum_{i=1}^n X_i e_i = 0$ . This can be shown from the definition

$$\begin{aligned} \sum_{i=1}^n X_i e_i &= \sum_{i=1}^n X_i (Y_i - \hat{Y}_i) \\ &= \sum_{i=1}^n X_i (Y_i - b_0 - b_1 X_i) \\ &= \sum_{i=1}^n X_i Y_i - b_0 \sum_{i=1}^n X_i - b_1 \sum_{i=1}^n X_i^2 \\ &= b_0 \sum_{i=1}^n X_i + b_1 \sum_{i=1}^n X_i - b_0 \sum_{i=1}^n X_i - b_1 \sum_{i=1}^n X_i \\ &= 0 \end{aligned}$$

This is significant because it tells us that the dot product between the vector of explanatory variables  $\vec{X} = (X_1, \dots, X_n)^T$  is orthogonal to the

vector of error terms  $\vec{e} = (e_1, \dots, e_n)^T$ , and from the previous property we get that

$$\vec{e} \cdot \mathbf{1}_n = \sum_{i=1}^n e_i = 0$$

Hence the vectors  $\{1_n, X - \bar{X}1_n\}$  are linearly independent and form a basis of the estimation space.

(iv) By applying the Pythagorean Theorem to the previous property we get

$$\begin{aligned} \|Y\|^2 &= \|\hat{Y}\|^2 + \|Y - \hat{Y}\|^2 \\ \sum_{i=1}^n Y_i^2 &= \sum_{i=1}^n \hat{Y}_i^2 + \sum_{i=1}^n e_i^2 \\ &= \sum_{i=1}^n \bar{Y}^2 + b_1^2 \sum_{i=1}^n (X_i - \bar{X})^2 + \sum_{i=1}^n e_i^2 \\ \implies \sum_{i=1}^n Y_i^2 - n\bar{Y}^2 &= b_1^2 \sum_{i=1}^n (X_i - \bar{X})^2 + \sum_{i=1}^n e_i^2 \\ \sum_{i=1}^n (Y_i - \bar{Y})^2 &= b_1^2 \sum_{i=1}^n (X_i - \bar{X})^2 + \sum_{i=1}^n (Y_i - \hat{Y}_i)^2 \end{aligned}$$

This shows us the the total sum of squares is equal to the regression sum of squares plus the error sum of squares.

(v) The point  $(\bar{X}, \bar{Y})$  is on the fitted line.

(vi) The sum of residuals weighted by their corresponding fitted value is 0, that is

$$\sum_{i=1}^n y_i e_i = 0$$

(vii) Under the normality assumption,  $e_i \stackrel{\text{iid}}{\sim} N(0, \sigma^2)$ . The method of maximum likelihood leads to the method of least squares.

$$L(\beta_0, \beta_1, \sigma^2) = \left( \frac{1}{\sqrt{2\pi}\sigma} \right)^n \exp \left( -\frac{1}{2\sigma^2} \sum_{i=1}^n \epsilon_i^2 \right)$$

So maximizing  $L(\beta_0, \beta_1, \sigma^2)$  is equivalent to minimizing  $\sum \epsilon_i^2$ .

### 2.1.3 Estimation of $\sigma^2$

We need to estimate  $\sigma^2$  to test hypotheses and construct interval estimates pertinent to the regression model. Ideally we would like this estimate not to depend on the adequacy of the fitted model. This is only possible when there are several observations on  $y$  for at least one value of  $x$ , or when prior information

concerning  $\sigma^2$  is available. When this approach cannot be used, the estimate of  $\sigma^2$  is obtained from the residual or error sum of squares.

$$SSE = \sum_{i=1}^n e_i^2 = \sum_{i=1}^n (y_i - \hat{y}_i)^2$$

We can substitute  $\hat{y}_i$  for  $b_0 + b_1 x_i$  and simplify to get

$$SSE = \sum_{i=1}^n y_i^2 - n\bar{y}^2 - b_1 S_{xy}$$

Moreover, the correct sum of squares of the response variable is

$$SST = \sum_{i=1}^n y_i^2 - n\bar{y}^2 = \sum_{i=1}^n (y_i - \bar{y})^2$$

Thus,

$$SSE = SST - b_1 S_{xy}$$

The residual sum of squares has  $n - 2$  degrees of freedom, because we reserve 2 degrees of freedom for the estimators  $b_0$ ,  $b_1$ . We will later show that the expected value for  $SSE$  is

$$E(SSE) = (n - 2)\sigma^2$$

So an unbiased estimator of  $\sigma^2$  is

$$\hat{\sigma}^2 = \frac{SSE}{n - 2} = MSR$$

The quantity  $MSR$  is known as the **residual mean square**. The root of  $\hat{\sigma}^2$  is known as the **standard error of regression**.

## 2.2 Hypothesis Testing on the Slope and Intercept

To perform hypotheses tests and construct confidence intervals, we require that we make the additional assumption that the model errors  $\epsilon_i$  are normally distributed. Thus, the complete assumptions are that the errors are normally and independently distributed with mean 0 and variance  $\sigma^2$ , written as  $\{\epsilon_i\} \stackrel{\text{iid}}{\sim} N(0, \sigma^2)$ . We will discuss how these assumptions can be checked through residual analysis later.

Suppose that we have the model  $Y_i = \beta_0 + \beta_1 X_i + \epsilon_i$ , where  $\{\epsilon_i\} \stackrel{\text{iid}}{\sim} N(0, \sigma^2)$ . Then

$$(a) \quad \frac{b_1 - \beta_1}{se(b_1)} \sim t_{n-2} \text{ where } se^2(b_1) = \frac{MSE}{\sum_{i=1}^n (X_i - \bar{X})^2}$$

(b)  $\frac{b_0 - \beta_0}{se(b_0)} \sim t_{n-2}$  where

$$se^2(b_0) = MSE \left( \frac{1}{n} + \frac{\bar{X}^2}{\sum_{i=1}^n (X_i - \bar{X})^2} \right)$$

(c) MSE is an unbiased estimate of  $\sigma^2$  and is independent of  $b_0, b_1$ . Furthermore

$$\frac{(n-2)MSE}{\sigma^2} \sim \chi_{n-2}^2$$

*Proof.* Proof will be shown when we generalize this using matrices in later sections.  $\square$

### 2.2.1 Using $t$ -tests

Suppose we want to test that the slope is equal to a constant,  $\beta$ , we have the hypotheses

$$H_0 : \beta_1 = \beta, H_1 : \beta_1 \neq \beta$$

Since  $\{\epsilon_i\} \stackrel{\text{iid}}{\sim} N(0, \sigma^2)$ , the observations  $y_i$  are normally distributed with  $\beta_0 + \beta_1 x_i$  and variance  $\sigma^2$ . Then,  $b_1$  is a linear combination of the observations, so it is normally distributed with mean  $\beta_1$  and variance  $\sigma^2/S_{xx}$ . Therefore, our test statistic becomes

$$Z_0 = \frac{b_1 - \beta}{\sqrt{\sigma^2/S_{xx}}}$$

If the null hypothesis is true, then  $Z_0 \sim N(0, 1)$ . If  $\sigma^2$  is known then we would use  $Z_0$  to test our hypotheses. However,  $\sigma^2$  is typically unknown. We've seen that  $MSE$  is an unbiased estimator for  $\sigma^2$ , and we've established that  $(n-2)MSE/\sigma^2 \sim \chi_{n-2}^2$ .

$$t_0 = \frac{b_1 - \beta}{\sqrt{MSE/S_{xx}}}$$

If the null hypothesis is true,  $t_0 \sim t_{n-2}$ . We compare the observed value  $t_0$  with the upper  $\alpha/2$ , of the  $t_{n-2}$  distribution. So we reject the null hypothesis

$$|t_0| > t_{\alpha/2, n-2}$$

We can also test with the  $p$ -value. From the equation for  $t_0$ , the denominator is called the **estimated standard error** of the slope.

$$se(b_1) = \sqrt{\frac{MSE}{S_{xx}}}$$

So, we often write  $t_0$  is

$$t_0 = \frac{b_1 - \beta}{se(\beta_1)}$$

We test the intercept in a similar manner,

$$H_0 : \beta_0 = \beta, H_1 : \beta_0 \neq \beta$$

We use a similar test statistic,

$$t_0 = \frac{b_0 - \beta}{se(b_0)}$$

and we reject the null hypothesis when  $|t_0| > t_{\alpha/2, n-2}$ .

### 2.2.2 Testing Significance

A special case for hypotheses is

$$H_0 : \beta_1 = 0, H_1 : \beta_1 \neq 0$$

These hypotheses relate to the **significance of regression**. Failing to reject the null hypothesis means there is no linear relationship between  $x$  and  $y$ , we would reject the null hypothesis when  $|t_0| > t_{\alpha/2, n-2}$ .

### 2.2.3 Analysis of Variance Tables (ANOVA)

**Analysis of variance** can be used to test significance of regression. The analysis of variance of variance is based on a partitioning of the total variability of the response variable  $y$ , given by

$$y_i - \bar{y} = (\hat{y}_i - \bar{y}) + (y_i - \hat{y}_i)$$

Then, taking the sum of the square of both sides

$$\sum_{i=1}^n (y_i - \bar{y})^2 = \sum_{i=1}^n (\hat{y}_i - \bar{y})^2 + \sum_{i=1}^n (y_i - \hat{y}_i)^2 + 2 \sum_{i=1}^n (\hat{y}_i - \bar{y})(y_i - \hat{y}_i)$$

Notice that

$$\begin{aligned} 2 \sum_{i=1}^n (\hat{y}_i - \bar{y})(y_i - \hat{y}_i) &= 2 \sum_{i=1}^n \hat{y}_i (y_i - \hat{y}_i) - 2\bar{y} \sum_{i=1}^n (y_i - \hat{y}_i) \\ &= 2 \sum_{i=1}^n \hat{y}_i e_i - 2\bar{y} \sum_{i=1}^n e_i = 0 \end{aligned}$$

Therefore,

$$\sum_{i=1}^n (y_i - \bar{y})^2 = \sum_{i=1}^n (\hat{y}_i - \bar{y})^2 + \sum_{i=1}^n (y_i - \hat{y}_i)^2$$

The left side is the corrected sum of squares of the observations, which we denote by  $SST$  or  $SSTO$ . Notice that  $y_i - \hat{y}_i = e_i$ , so that term is the sum of residuals squared  $SSE$ . We call  $\sum_{i=1}^n (\hat{y}_i - \bar{y})^2$  the **regression sum of squares**.

So we have

$$SST = SSR + SSE$$

The regression sum of squares can also be computed by

$$SSR = b_1^2 S_{xx}$$

The **degrees of freedom** for each sum of squares is as follows.

- The total sum of squares  $SST$  has  $df_T = n - 1$  since we lose a degree of freedom for the constraint

$$\sum_{i=1}^n (y_i - \bar{y}) = 0$$

- The regression sum of squares  $SSR$  has  $df_R = p - 1$  where  $p$  is the number of variables (including  $y$ ).
- The residual sum of squares  $SSE$  has  $df_E = n - 2$  degrees of freedom since 2 constraints are placed on  $e_i = y_i - \hat{y}_i$  with the estimation for  $\beta_0$  and  $\beta_1$ .

We create a table to summarize our results from statistical analysis.

| Source     | SS                                   | DF      | MS=SS/df | E(MS)   |
|------------|--------------------------------------|---------|----------|---|
| Regression | $SSR = b_1^2 \sum (X_i - \bar{X})^2$ | $p - 1$ | MSR      | $\sigma^2 + \beta_1^2 \sum (X_i - \bar{X})^2$ |
| Error      | $SSE = \sum (Y_i - \hat{Y}_i)^2$     | $n - p$ | MSE      | $\sigma^2$                                    |
| Total      | $SSTO = \sum (Y_i - \bar{Y})^2$      | $n - 1$ |          |   |

Each of the sums of squares is a quadratic form where the rank of the corresponding matrix is the degrees of freedom indicated. Chochran's theorem applies and we conclude that the quadratic forms are independent and have chi-squared distributions. Note that

$$\frac{SSR}{\sigma^2} = \frac{b_1^2 \sum (X_i - \bar{X})^2}{\sigma^2} \sim \chi_{p-1}^2$$

$$\frac{SSE}{\sigma^2} = \frac{\sum (Y_i - \hat{Y}_i)^2}{\sigma^2} \sim \chi_{n-p}^2$$



Then, the ratio between 2 chi-squared distributions divided by their degrees of freedom has a F-distribution with their respective degrees of freedom.

$$F = \frac{SSR/\sigma^2(p-1)}{SSE/\sigma^2(n-p)} = \frac{SSR/(p-1)}{SSE/(n-p)} = \frac{MSR}{MSE} \sim F_{p-1, n-p}$$

The degrees of freedom are determined by the amount of data required to calculate each expression.

To summarize, the ANOVA table indicates how one can test the null hypothesis

$$H_0 : \beta_1 = 0$$

$$H_1 : \beta_1 \neq 0$$

The null Hypothesis is that the slope of the line is equal to 0. Under the null hypothesis, the expected mean square for regression and the expected mean square error are separate independent estimates of the variance  $\sigma^2$ .

## 2.3 Interval Estimation

### 2.3.1 Confidence Intervals on $\beta_0$ , $\beta_1$ , and $\sigma^2$ .

The width of the confidence intervals are a measure of the quality of the regression line. If the error is normally and independently distributed by our assumption, then  $(b_1 - \beta_1)/se(b_1)$  and  $(b_0 - \beta_0)/se(b_0)$  follow a  $t$  distribution with  $n - 2$  degrees of freedom. So, a  $100(1 - \alpha)$  percent. The confidence interval for the slope  $\beta_1$  is

$$b_1 - t_{\alpha/2, n-2}se(b_1) \leq b_1 \leq b_1 + t_{\alpha/2, n-2}se(b_1)$$

and for the intercept  $\beta_0$ ,

$$b_0 - t_{\alpha/2, n-2}se(b_0) \leq b_0 \leq b_0 + t_{\alpha/2, n-2}se(b_0)$$

The interpretation for these intervals is, if we were to take repeated samples of the same size at the same  $x$  levels and construct 95% CIs on the slope for each sample, then 95% of those intervals will contain the true value of  $\beta_1$ .

As we've seen earlier, the sampling distribution of  $(n - 2)MSE/\sigma^2$  follows a chi-square distribution with  $n - 2$  degrees of freedom, so

$$P \left\{ \chi_{1-\alpha/2, n-2}^2 \leq \frac{(n-2)MSE}{\sigma^2} \leq \chi_{\alpha/2, n-2}^2 \right\}$$

Thus the  $100(1 - \alpha)$  percent CI on  $\sigma^2$  is

$$\frac{(n-2)MSE}{\chi_{\alpha/2, n-2}^2} \leq \sigma^2 \leq \frac{(n-2)MSE}{\chi_{1-\alpha/2, n-2}^2}$$

### 2.3.2 Interval Estimation of the mean Response

Another important part of the regression model is estimating the mean response  $E(y)$  for a particular regressor variable  $x$ . Assuming that  $x_0$  is any value of the regressor variable within the range of the original data on  $x$  that we used to create the model. Then, an unbiased estimator for  $E(y|x_0)$  can be found from the fitting model

$$\widehat{E(y|x_0)} = \hat{\mu}_{y|x_0} = b_0 + b_1x_0$$

Note that  $\hat{\mu}_{y|x_0}$  follows a normal distribution since it is a linear combination of the observations  $y_i$ . The variance is

$$\text{Var}(\hat{\mu}_{y|x_0}) = \text{Var}(b_0 + b_1x_0) = \text{Var}(\bar{y} - b_1(x_0 - \bar{x})) = \frac{\sigma^2}{n} + \frac{\sigma^2(x_0 - \bar{x})^2}{S_{xx}}$$

The sampling distribution for

$$\frac{\hat{\mu}_{y|x_0} - E(y|x_0)}{\sqrt{MSE(1/n + (x_0 - \bar{x})^2/S_{xx})}}$$

is a  $t$  distribution with  $n - 2$  degrees of freedom. Then the CI is given as

$$\left[ \hat{\mu}_{y|x_0} \pm t_{\alpha/2, n-2} \sqrt{MSE \left( \frac{1}{n} + \frac{(x_0 - \bar{x})^2}{S_{xx}} \right)} \right]$$

## 2.4 Coefficient of Determination

The quantity

$$R^2 = \frac{SSR}{SST} = 1 - \frac{SSE}{SST}$$

is called the **coefficient of determination**.  $R^2$  is also called the proportion of variation explained by the regressor  $x$  since  $SST$  is a measure of variability in  $y$  without considering the effect of  $x$ , and  $SSE$  is the variability in  $y$  after considering  $x$ . Since  $0 \leq SSE \leq SST$ , then  $0 \leq R^2 \leq 1$ . An  $R^2$  value close to 1 means **most of the variability of  $y$  is explained by  $x$** .

## 2.5 Correlation Coefficient

The pearson correlation coefficient, denoted by  $\rho$ , related to  $b_1$  is given as

$$\rho = \frac{\text{Cov}(X, Y)}{\sqrt{\text{Var}(X)}\sqrt{\text{Var}(Y)}}$$

This measures the linear correlation between 2 variables. When applied to a sample,

$$r = b_1 \left( \frac{S_{xx}}{SST} \right)^{\frac{1}{2}} = \frac{\sum_{i=1}^n (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^n (X_i - \bar{X})^2} \sqrt{\sum_{i=1}^n (Y_i - \bar{Y})^2}} = \frac{S_{xy}}{(S_{xx}SST)^{1/2}}$$

Note that  $-1 \leq r \leq 1$ . To test hypotheses on  $\rho$ , we have 2 cases. The hypotheses for testing if the correlation is 0 is as follows

$$H_0 : \rho = 0, \quad H_1 : \rho \neq 0$$

When testing the null hypothesis  $\rho = 0$ , we use a  $t$  statistic given as

$$t = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}} \sim t_{n-2}$$

When testing

$$H_0 : \rho = \rho_0, \quad H_1 : \rho \neq \rho_0$$

We use a  $Z$  statistic,

$$Z = \operatorname{arctanh} r = \frac{1}{2} \ln \left( \frac{1+r}{1-r} \right) \sim N \left( \mu_z, \frac{1}{n-3} \right)$$

where

$$\mu_z = \frac{1}{2} \ln \left( \frac{1+\rho}{1-\rho} \right)$$

Now we can standardize our statistic to obtain a standard normal test statistic

$$Z_0 = (\operatorname{arctanh}(r) - \operatorname{arctanh}(\rho_0))\sqrt{n-3}$$

We can obtain our confidence interval with

$$\tanh \left( \operatorname{arctanh}(r) - \frac{Z_{\alpha/2}}{\sqrt{n-3}} \right) \leq \rho \leq \tanh \left( \operatorname{arctanh}(r) + \frac{Z_{\alpha/2}}{\sqrt{n-3}} \right)$$

where  $\tanh(u) = (e^u - e^{-u})/(e^u + e^{-u})$ .

## Chapter 3

# Multiple Linear Regression

We call a regression model with more than one regressor variable a **multiple regression model**.

### 3.1 Matrix Approach to Regression

We will first cover simple linear regression in matrix form.

Let  $Y = [Y_1, \dots, Y_n]^T$  be a column data vector, and we'll define the expected value as

$$E(Y) = \begin{bmatrix} E(Y_1) \\ \vdots \\ E(Y_n) \end{bmatrix}$$

**Proposition 3.1.1.** *If  $Z = AY + B$  for a matrix of constants  $A$ , and  $B$ , then*

$$E(Z) = AE(Y) + B$$

*Proof.* Simply from the definition of expectations on vectors,

$$E(Z_i) = E \left( \left[ \sum_j a_{ij} Y_j \right] + b_i \right) = \sum_j a_{ij} E(Y_j) + b_i$$

So

$$E(Z) = AE(Y) + B$$

□

**Definition 3.1.1.** *The covariance of a vector of data*

$$Y = \begin{bmatrix} Y_1 \\ \vdots \\ Y_n \end{bmatrix}$$

is

$$\text{Cov}(Y) = E([Y - E(Y)][Y - E(Y)]^T) = \Sigma$$

**Proposition 3.1.2.**  $\text{Cov}(AY) = A\Sigma A^T$ .

**Definition 3.1.2.** *A random vector  $Y$  has a multivariate normal distribution if its density is given by*

$$f(y_1, \dots, y_n) = \frac{|\Sigma|^{-1/2}}{\exp\left(-\frac{1}{2}(Y - \mu)^T \Sigma^{-1}(Y - \mu)\right)}$$

where

$$Y^T = (y_1, \dots, y_n), \quad \mu^T = (\mu_1, \dots, \mu_n)$$

we denote this by

$$Y \sim N_n(\mu, \Sigma)$$

**Theorem 3.1.1.** *Let  $Y \sim N_n(\mu, \Sigma)$ . Let  $A$  be an arbitrary  $p \times n$  matrix of constants. Then*

$$Z = AY + B \sim N_p(A\mu + B, A\Sigma A^T)$$

This theorem implies that any linear combination of normal variates has a normal distribution. This theorem won't be proved here.

### 3.1.1 Derivatives

- $z = a'y \rightarrow \frac{\partial z}{\partial y} = a$
- $z = y'y \rightarrow \frac{\partial z}{\partial y} = 2y$
- $z = a' Ay \rightarrow \frac{\partial z}{\partial y} = A'a$
- $z = y' Ay \rightarrow \frac{\partial z}{\partial y} = A'y + Ay$
- If  $A$  is symmetric, then  $z = y' Ay \rightarrow \frac{\partial z}{\partial y} = 2A'y$

## 3.2 Multiple Regression Models

Suppose we have 2 regressor variables, a multiple regression model that may describe a relationship with our data is

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \epsilon$$

The parameter  $\beta_1$  indicates the expected change in response per unit change in  $x_1$  when  $x_2$  is held constant. Similarly  $\beta_2$  measures the change in  $y$  per unit change in  $x_2$  when  $x_1$  is held constant.

### 3.2.1 Least Squares Estimation of Regression Coefficients

The method of **least squares** can be used to estimate the regression coefficients. Suppose  $n > k$  observations are available, and let  $y_i$  denote the  $i$ th observed response  $x_{ij}$  denote the  $i$ th observation or level of regressor. We can write the sample regression model as

$$y_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \cdots + \beta_k x_{ik} + \epsilon_i = \beta_0 + \sum_{j=1}^k \beta_j x_{ij} + \epsilon_i$$

for  $i = 1, 2, \dots, n$ . Then the least squares function is

$$S(\beta_0, \beta_1, \dots, \beta_k) = \sum_{i=1}^n \epsilon_i = \sum_{i=1}^n \left( y_i - \beta_0 - \sum_{j=1}^k \beta_j x_{ij} \right)^2$$

Similar to the simple linear regression approach with  $Q$ , we want to minimize  $S$  with respect to  $\beta_0, \beta_1, \dots, \beta_k$ . So the least squares estimators must satisfy

$$\left. \frac{\partial S}{\partial \beta_0} \right|_{\hat{\beta}_0, \dots, \hat{\beta}_k} = -2 \sum_{i=1}^n \left( y_i - \hat{\beta}_0 - \sum_{j=1}^k \beta_j x_{ij} \right) = 0$$

and similarly for the rest of the estimators for  $\beta_j$  for  $j = 1, \dots, k$ .

$$\left. \frac{\partial S}{\partial \beta_j} \right|_{\hat{\beta}_0, \dots, \hat{\beta}_k} = -2 \sum_{i=1}^n \left( y_i - \hat{\beta}_0 - \sum_{j=1}^k \beta_j x_{ij} \right) x_{ij} = 0$$

When simplifying these equations, we get the least squares **normal equations**, which we will put in terms of matrices later on.

$$\begin{aligned} n\hat{\beta}_0 + \hat{\beta}_1 \sum_{i=1}^n x_{i1} + \hat{\beta}_2 \sum_{i=1}^n x_{i2} + \cdots + \hat{\beta}_k \sum_{i=1}^n x_{ik} &= \sum_{i=1}^n y_i \\ \hat{\beta}_0 \sum_{i=1}^n x_{i1} + \hat{\beta}_1 \sum_{i=1}^n x_{i1}^2 + \hat{\beta}_2 \sum_{i=1}^n x_{i1}x_{i2} + \cdots + \hat{\beta}_k \sum_{i=1}^n x_{ik}x_{i1} &= \sum_{i=1}^n x_{i1}y_i \end{aligned}$$

$$\begin{aligned} & \vdots \\ \hat{\beta}_0 \sum_{i=1}^n x_{ik} + \hat{\beta}_1 \sum_{i=1}^n x_{i1}x_{ik} + \hat{\beta}_2 \sum_{i=1}^n x_{ik}x_{i2} + \cdots + \hat{\beta}_k \sum_{i=1}^n x_{ik}^2 &= \sum_{i=1}^n x_{ik}y_i \end{aligned}$$

Note that there are  $p = k + 1$  normal equations for each of the unknown regression coefficients. The solutions give us the **least squares estimators**  $\hat{\beta}_0, \hat{\beta}_1, \dots, \hat{\beta}_k$ .

As mentioned earlier, it is easier to work with matrix notation, so we will express the model using matrices

$$Y = X\beta + \epsilon$$

where

$$Y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix}, \quad X = \begin{bmatrix} 1 & x_{11} & x_{12} & \cdots & x_{1k} \\ 1 & x_{21} & x_{22} & \cdots & x_{2k} \\ \vdots & \vdots & \vdots & & \vdots \\ 1 & x_{n1} & x_{n2} & \cdots & x_{nk} \end{bmatrix}$$

$$\beta = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ \beta_k \end{bmatrix}, \quad \epsilon = \begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \vdots \\ \epsilon_n \end{bmatrix}$$

In general,  $Y$  is an  $n \times 1$  vector of observations,  $X$  is an  $n \times p$  matrix of the levels of the regressor variables,  $\beta$  is a  $p \times 1$  vector of regression coefficients, and  $\epsilon$  is an  $n \times 1$  vector of random variables. Note that from here on out we will denote the transpose of a matrix  $A^T$  as  $A'$ . We want to find the vector of least squares estimators  $\hat{\beta}$  that minimizes

$$S(\beta) = \sum_{i=1}^n \epsilon_i^2 = \epsilon' \epsilon = (Y - X\beta)'(Y - X\beta)$$

This can be expanded as

$$S(\beta) = Y'Y - \beta'X'Y - Y'X\beta + \beta'X'X\beta = Y'Y - 2\beta'X'Y + \beta'X'X\beta$$

This is derived from using the fact that  $\beta'X'Y$  is a  $1 \times 1$  matrix, so it is a scalar and its transpose is the same. Now our equation must satisfy

$$\left. \frac{\partial S}{\partial \beta} \right|_{\hat{\beta}} = -2X'Y + 2X'X\hat{\beta} = 0$$

This gives us

$$X'X\hat{\beta} = X'Y$$

The equations here are our **least-squares** normal equations. They are the same as the previous equations we found earlier not in matrix form.

We can solve the normal equations by multiplying both sides of our equation by  $X'X$  to give us

$$\hat{\beta} = (X'X)^{-1}X'Y$$

provided that the inverse exists.

The fitted regression model corresponding to the levels of regressor variables  $x' = [1, x_1, x_2, \dots, x_k]$  is then

$$\hat{y} = x'\hat{\beta} = \hat{\beta}_0 + \sum_{j=1}^k \hat{\beta}_j x_j$$

So the vector of fitted values  $\hat{y}_i$  corresponding to the observed values  $y_i$  is

$$\hat{Y} = X\hat{\beta} = X(X'X)^{-1}X'Y = HY$$

The  $n \times n$  matrix  $H = X(X'X)^{-1}X'$  is known as the **hat matrix**. It maps the vector of observed values to a vector of fitted values (in other words, it "puts the hat" on  $Y$ ).

### 3.2.2 Properties of the Hat Matrix $H$

The hat matrix has some useful properties, notably

- (a)  $H$  is a projection matrix, so it is idempotent and symmetric

$$HH = H$$

$$H' = H$$

- (b) The matrix  $H$  is orthogonal to the matrix  $I - H$ , so

$$(I - H)H = H - HH = 0$$

Moreover,  $(I - H)$  is idempotent and a project matrix as well.

- (c) The vector of residuals, which we will denote as  $\vec{e}$ , is given as

$$\vec{e} = Y - \hat{Y} = Y - HY = (I - H)Y$$

- (d) Properties (b) and (c) imply that the observation vector  $Y$  is projected onto a space spanned by the columns of  $H$ , and the residuals are in an orthogonal space (similar to the case for the simple linear regression model).

$$Y = HY + (I - H)Y$$



- (e) Similar to our simple linear model, we can apply the pythagorean theorem (from the fact that the matrices are orthogonal) to obtain

$$\|Y\|^2 = \|HY\|^2 + \|(I - H)Y\|^2$$

We will see later why expressing

$$\vec{e} = Y - X\hat{\beta} = Y - HY = (I - H)Y$$

is useful.

### 3.2.3 Properties of the Least-Squares Estimators

We can first show that  $\hat{\beta}$  is an unbiased estimators,

$$\begin{aligned} E(\hat{\beta}) &= E[(X'X)^{-1}X'Y] \\ &= E[(X'X)^{-1}X'(X\beta + \epsilon)] \\ &= E[(X'X)^{-1}X'X\beta + X'\epsilon] \\ &= E[\beta + \epsilon] \\ &= E(\beta) + E(\epsilon) \\ &= \beta \end{aligned}$$

This is using the fact that  $E(\epsilon) = 0$ . So if our model assumptions hold,  $\hat{\beta}$  is an unbiased estimator for  $\beta$ .

The variance of  $\hat{\beta}$  is expressed by the covariance matrix

$$\text{Cov}(\hat{\beta}) = E\left\{[\hat{\beta} - E(\hat{\beta})][\hat{\beta} - E(\hat{\beta})]^T\right\}$$

### 3.2.4 Estimation of $\sigma^2$

We may develop an estimator for  $\sigma^2$  using the residual sum of squares,

$$SSE = \sum_{i=1}^n (y_i - \hat{y}_i)^2 = \sum_{i=1}^n e_i^2 = e'e$$

Then, we can substitute  $e = Y - X\hat{\beta}$ ,

$$\begin{aligned} SSE &= (Y - X\hat{\beta})'(Y - X\hat{\beta}) \\ &= Y'Y - \hat{\beta}'X'Y - Y'X\hat{\beta} + \hat{\beta}'X'X\hat{\beta} \\ &= Y'Y - 2\hat{\beta}'X'Y + \hat{\beta}'X'X\hat{\beta} \end{aligned}$$

Then since  $X'X\hat{\beta} = X'y$ , we get

$$SSE = Y'Y - \hat{\beta}'X'Y$$

It can be shown that  $SSE$  has  $n - p$  degrees of freedom since  $p$  parameters are estimated in the regression model. This gives us the **residual mean square** or **mean square error**

$$MSE = \frac{SSE}{n - p}$$

It can be shown that  $MSE$  is again an unbiased estimator for  $\sigma^2$ , therefore

$$\hat{\sigma}^2 = MSE$$

### 3.3 Estimation and Hypothesis Testing in Multiple Linear Regression

The true relationship between  $y$  and our regressors  $x_1, \dots, x_k$  is unknown, and our multiple linear regression model is used to approximate this. Models sometimes are more complex in structure than the model we've discussed,

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_k x_k + \epsilon$$

but we can still use a multiple linear regression model. For example, consider a cubic polynomial model

$$y = \beta_0 + \beta_1 x + \beta_2 x^2 + \beta_3 x^3 + \epsilon$$

If we set  $x_1 = x$ ,  $x_2 = x^2$ , and  $x_3 = x^3$ , we can rewrite the equation as

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \epsilon$$

Models that include **interaction effects** may also be analyzed by multiple linear regression methods. For example if we have the model

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2 + \epsilon$$

we can set  $x_3 = x_1 x_2$ , and  $\beta_3 = \beta_{12}$ , then we get

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \epsilon$$

Finally, consider a **second-order model with interaction**

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{12} x_1 x_2 + \epsilon$$

We can set  $x_3 = x_1^2$ ,  $x_4 = x_2^2$ ,  $x_5 = x_1 x_2$ ,  $\beta_3 = \beta_{11}$ ,  $\beta_4 = \beta_{22}$ , and  $\beta_5 = \beta_{12}$ , then we can get our linear model

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \epsilon$$

Our predictor variables may also be qualitative, for example

$$X = \begin{cases} 0 & \text{if subject is male} \\ 1 & \text{if subject is female} \end{cases}$$

We could also have a transformed response variable

$$\ln Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \epsilon_i$$

Now we want to be able to ask questions about our models adequacy and which regressors are important. To do this, we can conduct various hypothesis tests which also require that our random errors are independent and identically distributed from a normal distribution with mean  $E(\epsilon_i) = 0$ , and variance  $\text{Var}(\epsilon_i) = \sigma^2$ .

### 3.3.1 Testing for Significance of Regression

The test for **significance of regression** is to determine if there is a linear relationship between the response  $Y$  and any of the regressors  $x_1, \dots, x_k$ . The appropriate hypotheses are

$$H_0 : \beta_1 = \beta_2 = \dots = \beta_k = 0, \quad H_1 : \beta_j \neq 0$$

for *at least one* value of  $j$ . Rejection of the null hypothesis implies *at least one* of the regressors contribute significantly to the model. The test is a generalization of the analysis of variance used in simple regression. We define the sum of squares the same way,

$$SST = SSR + SSE$$

If the null hypothesis is true, then  $SSR/\sigma^2 \sim \chi_k^2$ , where  $k$  is the number of regressors in the model ( $p - 1$ ). Similarly,  $SSE/\sigma^2 \sim \chi_{n-k-1}^2$  if the null hypothesis holds and it can be shown that  $SSR/\sigma^2$  is independent of  $SSE/\sigma^2$ . We then use an  $F$  statistic

$$F_0 = \frac{SSR/k}{SSE/(n-k-1)} = \frac{MSR}{MSE} \sim F_{k, n-k-1}$$

which follows an  $F$  distribution. Then, we reject the null hypothesis  $H_0 : \beta_1 = \beta_2 = \dots = \beta_k = 0$  if

$$F_0 > F_{\alpha, k, n-k-1}$$

We can construct an analysis of variance table to summarize this procedure again.

| Source of Variation | Sum of Squares | DF          | Mean Square | $F$ -statistic |
|---------------------|----------------|-------------|-------------|----------------|
| Regression          | SSR            | $k$         | MSR         | $MSR/MSE$      |
| Residuals           | SSE            | $n - k - 1$ | MSE         |                |
| Total               | SST            | $n - 1$     |             |                |

The **total sum of squares** is

$$SST = \sum_{i=1}^n Y_i^2 - \frac{1}{n} \left( \sum_{i=1}^n Y_i \right)^2 = Y'Y - \frac{1}{n} \left( \sum_{i=1}^n Y_i \right)$$

The **regression sum of squares** is

$$SSR = \hat{\beta}' X'Y - \frac{1}{n} \left( \sum_{i=1}^n Y_i \right)$$

The **residual sum of squares** is

$$SSE = Y'Y - \hat{\beta}' X'Y = Y'(I - H)Y$$

We can show that  $Y'J_nY = \left( \sum_{i=1}^n Y_i \right)^2$  where  $J_n$  is the matrix with 1 in every entry

$$\begin{aligned} Y'J_nY &= \begin{bmatrix} Y_1 & \cdots & Y_n \end{bmatrix} \begin{bmatrix} 1 & \cdots & 1 \\ \vdots & \ddots & \vdots \\ 1 & \cdots & 1 \end{bmatrix} \begin{bmatrix} Y_1 \\ \vdots \\ Y_n \end{bmatrix} \\ &= \begin{bmatrix} \sum Y_i & \cdots & \sum Y_i \end{bmatrix} \begin{bmatrix} Y_1 \\ \vdots \\ Y_n \end{bmatrix} \\ &= Y_1 \sum_{i=1}^n Y_i + Y_2 \sum_{i=1}^n Y_i + \cdots + Y_n \sum_{i=1}^n Y_i \\ &= \sum_{i=1}^n Y_i (Y_1 + Y_2 + \cdots + Y_n) \\ &= \left( \sum_{i=1}^n Y_i \right) \left( \sum_{i=1}^n Y_i \right) \\ &= \left( \sum_{i=1}^n Y_i \right)^2 \end{aligned}$$

Thus we can write

$$\begin{aligned}
SST &= \sum_{i=1}^n Y_i^2 - \frac{1}{n} \left( \sum_{i=1}^n Y_i \right)^2 \\
&= Y'Y - \frac{1}{n} Y' J_n Y \\
&= Y' \left( Y - \frac{1}{n} J_n Y \right) \\
&= Y' \left( I - \frac{1}{n} J_n \right) Y
\end{aligned}$$

It can be shown easily that we can write the regression sum of squares in terms of this matrix  $J_n$

$$SSR = Y' \left( H - \frac{1}{n} J_n \right) Y$$

### 3.3.2 Tests on Individual Regression Coefficients

Once we have determined that at least one of the regressors is significant, we can investigate which one (or more) is significant. Adding a variable to the model always causes the regression sum of squares to increase and the residual sum of squares to decrease. So we must decide whether the increase in  $SSR$  is sufficient to warrant using an additional regressor. The added regressor also increases the variance for the fitted value  $\hat{y}$ , so we must be careful to add only regressors that are significant. Adding an unimportant regressor can increase the mean square error, which can decrease the usefulness of the model.

To test an individual regression coefficient, say  $\beta_j$ , we use the test

$$H_0 : \beta_j = 0, \quad H_1 : \beta_j \neq 0$$

If the null hypothesis is not rejected, then we can remove the corresponding regressor  $x_j$ . The **test statistic** for this hypothesis is

$$t_0 = \frac{\hat{\beta}_j}{\sqrt{\hat{\sigma}^2 C_{jj}}} = \frac{\hat{\beta}_j}{se(\hat{\beta}_j)}$$

Where  $C_{jj}$  is the diagonal element of the matrix  $(X'X)^{-1}$  corresponding to  $\beta_j$ . We reject the null hypothesis if

$$|t_0| > t_{\alpha/2, n-(k-1)}$$

### 3.3.3 Extra Sum of Squares Principle

We may also directly determine the contribution to the regression sum of squares of a regressor, say  $x_j$ , by using the **extra sum of squares method**. This procedure can also be used to investigate the contribution of a subset of the regressor

variables.

Consider the regression model with  $k$  regressors,

$$Y = X\beta + \epsilon$$

where  $Y$  is  $n \times 1$ ,  $X$  is  $n \times p$ ,  $\beta$  is  $p \times 1$ , and  $\epsilon$  is  $n \times 1$  with  $p = k + 1$ . We want to determine if some subset of  $r < k$  regressors contribute significantly to our model. We will partition the regression coefficients into 2 vectors,  $\beta_1$  is a  $(p - r) \times 1$  vector, and  $\beta_2$  is the  $r \times 1$  vector of coefficients we are trying to test. We want to test the following hypotheses

$$H_0 : \beta_2 = 0, H_1 : \beta_2 \neq 0$$

So our model will be rewritten as

$$Y = X\beta + \epsilon = X_1\beta_1 + X_2\beta_2 + \epsilon$$

where  $X_1$  is a  $n \times (p - r)$  matrix that are the columns of  $X$  associated with  $\beta_1$ , and  $X_2$  is an  $n \times r$  matrix with the columns of  $X$  associated with  $\beta_2$ . This is our **full model**.

For the full model, we have established that

$$\hat{\beta} = (X'X)^{-1}X'Y$$

and the regression sum of squares is

$$SSR(\beta) = \hat{\beta}'X'Y$$

which has  $k = p - 1$  degrees of freedom. We also have the residual mean square

$$MSE = \frac{Y'Y - \hat{\beta}'X'Y}{n - p} = \frac{SSE}{n - p}$$

To find the contribution of the regressors in  $\beta_2$ , we fit the model assuming the null hypothesis  $H_0 : \beta_2 = 0$  is true. This gives us the **reduced model**

$$Y = X_1\beta_1 + \epsilon$$

The least squares estimator for  $\beta_1$  in the reduced model is

$$\hat{\beta}_1 = (X_1'X_1)^{-1}X_1'Y$$

The regression sum of squares is

$$SSR(\beta_1) = \hat{\beta}_1'X_1'Y$$

which has  $k - r = p - 1 - r$  degrees of freedom. The regression sum of squares due to  $\beta_2$  given that  $\beta_1$  is already in the model is

$$SSR(\beta_2|\beta_1) = SSR(\beta) - SSR(\beta_1)$$

with  $(p - 1) - (p - 1 - r) = r$  degrees of freedom. This sum of squares is called the **extra sum of squares due to**  $\beta_2$  because it measures the increase in the regression sum of squares that results from adding  $x_{k-r+1}, x_{k-r+2}, \dots, x_k$  to the model with  $x_1, x_2, \dots, x_{k-r}$ . Now we have the extra sum of squares due to  $\beta_2$  is independent of mean square error, so the null hypothesis  $\beta_2 = 0$  can be tested with the following statistic,

$$F_0 = \frac{SSR(\beta_2|\beta_1)/r}{MSE}$$

If  $F_0 > F_{\alpha, r, n-p}$ , then we reject the null hypothesis and conclude that at least one of the parameters in  $\beta_2$  is not zero, and at least one of the regressors in  $X_2$  contributes significantly to the regression model. This is sometimes called a **partial F test** since it measures the contribution of regressors in  $X_2$  given that  $X_1$  is in the model.

If we want to compute the regression squares for multiple variables, say

$$SSR(\beta_2|\beta_1, \beta_0)$$

We compute it in the following way

$$SSR(\beta_2|\beta_1, \beta_0) = SSR(\beta_2, \beta_1, \beta_0) - SSR(\beta_1, \beta_0) = SSR(\beta_1, \beta_2|\beta_0) - SSR(\beta_1|\beta_0)$$

We can partition the regression sum of squares into marginal single degree of freedom components. For example, consider the model

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \epsilon$$

We can use the following identity,

$$SST = SSR(\beta_1, \beta_2, \beta_3|\beta_0) + SSE$$

We can then decompose the three degree of freedom regression sum of squares as

$$SSR(\beta_1, \beta_2, \beta_3|\beta_0) = SSR(\beta_1, \beta_0) + SSR(\beta_2|\beta_1, \beta_0) + SSR(\beta_3|\beta_2, \beta_1, \beta_0)$$

### 3.3.4 Testing the General Linear Hypothesis

Suppose that the null hypothesis we want to test is  $H_0 : T\beta = 0$  where  $T$  is an  $r \times p$  matrix such that only  $r$  of the  $p$  equations in  $T\beta = 0$  are independent. That is, the rows are the independent equations and will yield a  $r \times 1$  vector of coefficients we'd like to test. Recall the  $\beta$  is a  $p \times 1$  vector. The **full model** stays the same, with  $Y = X\beta + \epsilon$  and  $\hat{\beta} = (X'X)^{-1}X'Y$ , and the residual sum of squares is

$$SSE(FM) = Y'Y - \hat{\beta}'X'Y$$

which has  $n - p$  degrees of freedom. To obtain the **reduced model**, the  $r$  independent equations in  $T\beta = 0$  are used to solve for  $r$  of the regression

coefficients in the full model in terms of the  $p - r$  regression coefficient. This gives us the reduced model

$$Y = Z\gamma + \epsilon$$

where  $Z$  is an  $n \times (p - r)$  matrix, and  $\gamma$  is a  $(p - r) \times 1$  vector of the unknown regression coefficients. The estimator for  $\gamma$  is

$$\hat{\gamma} = (Z'Z)^{-1}Z'Y$$

and the residual sum of squares is

$$SSE(RM) = Y'Y - \hat{\gamma}Z'Y$$

which has  $n - p + r$  degrees of freedom. The reduced model has less parameters than the full model so  $SSE(RM) \geq SSE(FM)$ . Now to test the hypothesis  $H_0 : T\beta = 0$ , we use the difference in residual sum of squares, denoted by  $SSH$ ,

$$SSH = SSE(RM) - SSE(FM)$$

which has  $n - p + r - (n - p) = r$  degrees of freedom. This is known as the sum of squares due to the hypothesis. The test statistic here is then

$$F_0 = \frac{SSH/r}{SSE(FM)/(n - p)} \sim F_{r, n-p}$$

We reject  $H_0$  if  $F_0 > F_{\alpha, r, n-p}$ .

## 3.4 Lack of Fit of the Regression Model

Sometimes, we want to test whether or not our linear model is justified at all. This is different from testing if the slope is 0.

### 3.4.1 Test for Lack of Fit

Suppose we have  $n_i$  observations on the response at the  $i$ th level of the regressor  $x_i$  for  $i = 1, 2, \dots, m$ . Let  $y_{ij}$  denote the  $j$ th ( $j = 1, 2, \dots, n_i$ ) observation on the corresponding response variable. In total, there are

$$n = \sum_{i=1}^m n_i$$

observations. We partition the residual sum of squares

$$SSE = SS_{PE} + SS_{LOF}$$

Where  $SS_{PE}$  is the sum of squares due to **pure error** and  $SS_{LOF}$  is the sum of squares due to **lack of fit**. Note that we can partition  $SSE$  using the following,

$$y_{ij} - \hat{y}_i = (y_{ij} - \bar{y}_i) + (\bar{y}_i - \hat{y}_i)$$



$\bar{y}_i$  is the average from the  $n_i$  observations at  $x_i$ , then we can square and sum both sides of the equation to give us

$$\sum_{i=1}^m \sum_{j=1}^{n_i} (y_{ij} - \hat{y}_i)^2 = \sum_{i=1}^m \sum_{j=1}^{n_i} (y_{ij} - \bar{y}_i)^2 + \sum_{i=1}^m \sum_{j=1}^{n_i} (\bar{y}_i - \hat{y}_i)^2$$

This gives us that the pure error sum of squares is

$$SS_{PE} = \sum_{i=1}^m \sum_{j=1}^{n_i} (y_{ij} - \bar{y}_i)^2$$

Since there are  $n_i - 1$  degrees of freedom for pure error at each level  $x_i$  that gives us the total degrees of freedom for  $SS_{PE}$  as

$$\sum_{i=1}^m (n_i - 1) = n - m$$

The sum of squares due to lack of fit is

$$SS_{LOF} = \sum_{i=1}^m n_i (\bar{y}_i - \hat{y}_i)^2$$

This is a weighted sum of squared deviations between the mean response  $\bar{y}_i$  at each level  $x_i$  with its corresponding fitted value  $\hat{y}_i$ . If the fitted values are close to the average responses, then there is a strong indication the regression function is linear. There are  $m - 2$  degrees of freedom for  $SS_{LOF}$  since there are  $m$  levels and 2 degrees are reserved for estimating the 2 parameters  $\beta_0, \beta_1$  to compute  $\hat{y}_i$ . This gives us our test statistic

$$F^* = \frac{SS_{LOF}/(m-2)}{SS_{PE}/(n-m)} = \frac{MS_{LOF}}{MS_{PE}}$$

The expected value for  $MS_{PE}$  is  $\sigma^2$ , and for  $MS_{LOF}$  it is

$$E(MS_{LOF}) = \sigma^2 + \frac{\sum_{i=1}^n n_i [E(y_i) - \beta_0 - \beta_1 x_i]^2}{m-2}$$

If the regression function is linear, then  $E(y_i) = \beta_0 + \beta_1 x_i$  so  $E(MS_{LOF})$  is  $\sigma^2$ . So, we construct our hypotheses as

$$H_0 : E(y_i) = \beta_0 + \beta_1 x_i, \quad H_1 : E(y_i) \neq \beta_0 + \beta_1 x_i$$

and we reject the null hypothesis if  $F^* > F_{\alpha, m-2, n-m}$ . We can summarize these in another analysis of variance table,

| Source      | Sum of Squares   | DF      | Mean Square      | F                  |
|-------------|--|---------|------------------|--------------------|
| Regression  | $SSR = \sum_{i=1}^m \sum_{j=1}^{n_i} (y_{ij} - \hat{y}_i)^2$     | 1       | $SSR/1$          | $MSR/MSE$          |
| Residuals   | $SSE(R) = \sum_{i=1}^m \sum_{j=1}^{n_i} (y_{ij} - \hat{y}_i)^2$  | $n - 2$ | $SSE(R)/n - 2$   |                    |
| Lack of Fit | $SS_{LOF} = \sum_{i=1}^m n_i (\bar{y}_i - \hat{y}_i)^2$          | $m - 2$ | $SS_{LOF}/m - 2$ | $MS_{LOF}/MS_{PE}$ |
| Pure Error  | $SS_{PE} = \sum_{i=1}^m \sum_{j=1}^{n_i} (y_{ij} - \bar{y}_i)^2$ | $n - m$ | $SS_{PE}/n - m$  |                    |
| Total       | $\sum_{i=1}^m \sum_{j=1}^{n_i} (y_{ij} - \bar{y})^2$             | $n - 1$ |                  |                    |

It may be also useful to note that

$$E(SS_{LOF}) = \sigma^2 + \frac{\sum_{i=1}^m n_i (E(y_i) - \beta_0 - \beta_1 x_i)^2}{m - 2}$$

and  $E(SS)_{LOF} = \sigma^2$  when we fail to reject the null hypothesis  $H_0 : E(y_i) = \beta_0 + \beta_1 x_i$ , since the second term becomes 0, and

$$E(SS_{PE}) = \sigma^2$$

## 3.5 Confidence Intervals in Multiple Regression

### 3.5.1 Confidence Intervals on Regression Coefficients

We want to construct confidence intervals for the regression coefficients  $\beta_j$ . We use the same assumptions that  $\epsilon_i \stackrel{\text{iid}}{\sim} N(0, \sigma^2)$ . So our observations  $y_i$  are normally and independently distributed with mean

$$\beta_0 + \sum_{j=1}^k \beta_j x_{ij}$$

and variance  $\sigma^2$ .  $\hat{\beta}$  is a linear combination of the observations, so it follows a normal distribution with a mean vector  $\beta$  and covariance matrix  $\sigma^2(X'X)^{-1}$ . This implies that the marginal distribution for any  $\hat{\beta}_j$  is normal with mean  $\beta_j$  and variance  $\sigma^2 C_{jj}$  where  $C_{jj}$  is the  $j$ th diagonal entry in the matrix  $(X'X)^{-1}$ . Thus,

$$\frac{\hat{\beta}_j - \beta_j}{\sqrt{\hat{\sigma}^2 C_{jj}}} \sim t_{n-p}$$

So our  $100(1 - \alpha)$  percent confidence interval for  $\beta_j$  is

$$\hat{\beta}_j - t_{\alpha/2, n-p} \sqrt{\hat{\sigma}^2 C_{jj}} \leq \beta_j \leq \hat{\beta}_j + t_{\alpha/2, n-p} \sqrt{\hat{\sigma}^2 C_{jj}}$$

Recall that we refer to

$$se(\hat{\beta}_j) = \sqrt{\hat{\sigma}^2 C_{jj}}$$

as the standard error of  $\hat{\beta}_j$ .

### 3.5.2 Confidence Intervals On the Mean Response

We can also construct confidence intervals on a specific point, such as  $x_{01}, x_{02}, \dots, x_{0k}$ . We'll define the vector  $x_0$  as

$$x_0 = \begin{bmatrix} 1 \\ x_{01} \\ x_{02} \\ \vdots \\ x_{0k} \end{bmatrix}$$

The fitted value corresponding to this point is

$$\hat{y}_0 = x_0' \hat{\beta}$$

This is an unbiased estimator for  $E(y|x_0)$  since  $E(\hat{y}_0) = x_0' \beta = E(y|x_0)$ , and the variance is

$$\text{Var}(\hat{y}_0) = \sigma^2 x_0' (X'X)^{-1} x_0$$

Thus our confidence interval for the mean response  $E(y|x_0)$  is

$$\hat{y}_0 - t_{\alpha/2, n-p} \sqrt{\hat{\sigma}^2 x_0' (X'X)^{-1} x_0} \leq E(y|x_0) \leq \hat{y}_0 + t_{\alpha/2, n-p} \sqrt{\hat{\sigma}^2 x_0' (X'X)^{-1} x_0}$$

### 3.5.3 Simultaneous Confidence Intervals on Regression Coefficients

**Theorem 3.5.1** (Bonferroni Inequality). *For two events  $A_1, A_2$ , we have that*

$$P(A_1 \cup A_2) = P(A_1) + P(A_2) - P(A_1 \cap A_2) \leq P(A_1) + P(A_2)$$

*From DeMorgan's identity, we also have*

$$P(A_1^c \cap A_2^c) = 1 - P(A_1 \cup A_2) \geq 1 - P(A_1) - P(A_2)$$

*where  $A_1^c$  is the complement of  $A_1$ .*

If we define the events

$$A_1^c : \hat{\beta}_0 \pm t_{1-\alpha/2, n-2} s(\hat{\beta}_0)$$

$$A_2^c : \hat{\beta}_1 \pm t_{1-\alpha/2, n-2} s(\hat{\beta}_1)$$

where  $s(\hat{\beta}_0), s(\hat{\beta}_1)$  are the standard deviations of  $\hat{\beta}_0$  and  $\hat{\beta}_1$ . So the event  $(A_1^c \cap A_2^c)$  is the event that the intervals simultaneous cover  $\beta_0, \beta_1$ . From Bonferroni's Inequality, if we have  $P(A_1) = P(A_2) = \alpha$ , then

$$P(A_1^c \cap A_2^c) \geq 1 - P(A_1) - P(A_2) = 1 - 2\alpha$$

In general, if we have  $p$  parameters and each confidence interval has confidence,  $1 - \frac{\alpha}{p}$ , then

$$P\left(\bigcap_{i=1}^p A_i^c\right) \geq 1 - p \frac{\alpha}{p} = 1 - \alpha$$

## Chapter 4

# Model Adequacy

We've made various assumptions thus far, such as

1. The relationship between the response  $y$  and the regressors is linear
2. The error terms  $\epsilon$  are normally distributed with mean 0 and variance  $\sigma^2$ .
3. The errors are uncorrelated.

We want to check the validity of these assumptions.

### 4.1 Residual Analysis

Recall the definition for our observed residuals

$$e_i = y_i - \hat{y}_i$$

Their variance is estimated by

$$\frac{1}{n-p} \sum_{i=1}^n (y_i - \hat{y}_i)^2 = \frac{SSE}{n-p} = MSE$$

The residuals are not independent, however, as the  $n$  residuals have only  $n-p$  degrees of freedom associated with them. This nonindependence of the residuals has little effect on their use for model adequacy checking as long as  $n$  is not small relative to the number of parameters  $p$ .

#### 4.1.1 Checking for Normality

If the assumption of normality holds, a box plot of the residuals should indicate a symmetric box around the median of 0. A histogram of the residuals can also be used to examine normality. If the residuals follow a similar curve as a normal distribution, then it suggests that the normality assumption is reasonable.

The skewness and kurtosis can also help provide insight in this case, a normal distribution has a skewness of 0 and a kurtosis of 3. Finally, a quantile-quantile plot (also known as a qq-plot) compares the quantiles of the residual data with the quantiles from a normal distribution. We compute

$$E_k = \sqrt{MSE} \cdot \Phi^{-1} \left( \frac{k - 0.375}{n + 0.25} \right), \quad k = 1, \dots, n$$

Where  $\Phi$  is the standard normal, and we plot  $e_{(k)}$  vs  $E_k$  where  $e_{(k)}$  is the residual with rank  $k$ . Under normality, we would expect a straight line.

### 4.1.2 Checking Constant Variance

We use  $MSE$  as an estimate for approximating the variance of residual. We can improve the residual scaling by dividing the residuals  $e_i$  by the exact standard deviations for the  $i$ th residual. Recall that we can use the notion with the hat matrix  $H$  to write the vector of residuals as

$$\mathbf{e} = (I - H)\mathbf{Y}$$

where  $H = X(X'X)^{-1}X'$  is the hat matrix. Recall the properties of the hat matrix, namely that it is symmetric and idempotent, and  $I - H$  has the same properties. We can write the residuals as

$$\mathbf{e} = (I - H)(X\boldsymbol{\beta} + \boldsymbol{\epsilon}) = (I - H)\boldsymbol{\epsilon}$$

The covariance matrix of the residuals is

$$\text{Var}(\mathbf{e}) = \text{Var}[(I - H)\boldsymbol{\epsilon}] = (I - H) \text{Var}(\boldsymbol{\epsilon})(I - H)' = \sigma^2(I - H)$$

This gives us the variance of the  $i$ th residual as

$$\text{Var}(e_i) = \sigma^2(1 - h_{ii})$$

and the covariance between residuals  $e_i$  and  $e_j$  as

$$\text{Cov}(e_i, e_j) = -\sigma^2 h_{ij}$$

Now, we can studentize the residuals to obtain

$$r_i = \frac{e_i}{\sqrt{MSE(1 - h_{jj})}}$$

We can plot the studentized residuals vs fitted values to check for non-constancy of variance. The plot should show a random distribution of points. Conversely, non-constance variance would appear as a pattern, an increasing or decreasing collection of points. A scale-location plot can also be used to exam homogeneity, by plotting

$$\sqrt{|r_i|} \text{ vs } \hat{Y}_i$$

If the residuals lie in a narrow band around 0 then there are no evidence to suggest we need corrections. Otherwise, if the residuals show a pattern, either increasing or decreasing, this is a sign that variance is non constant. If a double-bow pattern appears, this is indication that the variance in the middle is larger than the variance at the extremes. If the residuals appear to have a quadratic relationship (i.e a parabola shape), there may be a nonlinear relation that the model has not accounted for.