Simple Linear Regression – Matrix Form

Q.1. A foam beverage insulator (beer hugger) manufacturer produces their product for firms that want their logo on beer huggers for marketing purposes. The firm’s cost analyst wants to estimate their cost function. She interprets \( \beta_0 \) as the fixed cost of a production run, and \( \beta_1 \) as the unit variable cost (or marginal cost). Based on \( n = 5 \) production runs she observes the following pairs \((X_i, Y_i)\) where \( X_i \) is the number of beer huggers produced in the \( i^{th} \) production run (in 1000s), and \( Y_i \) was the total cost of the run (in $1000).

<table>
<thead>
<tr>
<th>( i )</th>
<th>( X_{i} )</th>
<th>( Y_{i} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.00</td>
<td>4.00</td>
</tr>
<tr>
<td>2</td>
<td>5.00</td>
<td>6.50</td>
</tr>
<tr>
<td>3</td>
<td>4.00</td>
<td>5.00</td>
</tr>
<tr>
<td>4</td>
<td>6.00</td>
<td>7.00</td>
</tr>
<tr>
<td>5</td>
<td>7.00</td>
<td>7.50</td>
</tr>
</tbody>
</table>

Obtain the following matrices and vectors: \( X, Y, X'X, X'Y, (X'X)^{-1}, \hat{\beta}, \hat{Y}, e \)

Q.2. Give the expected values of \( SS_{\mu} = Y'PY \) and \( SSE = Y'(I - P)Y \)

Q.3. For the matrix form of simple linear regression:

p.3.a. Derive the least squares estimator of \( \beta \)

p.3.b. Give the mean vector and variance-covariance matrix for the estimator in p.3.a.

Q.4. For the matrix form of simple linear regression:

p.4.a. Write \( \hat{Y} \) and \( e \) as linear functions of \( Y \)

p.4.b. Show that \( P = X(X'X)^{-1}X' \) is symmetric and idempotent

p.4.c. Use p.4.a. and p.4.b. to show that \( \sum_{i=1}^{n} \hat{Y}_i e_i = \hat{Y}'e = 0 \)

Q.5. An engineer is interested in the relationship between steel thickness (\( X \)) and its breaking strength (\( Y \)). She obtains the following matrices from a matrix computer package:

\[
X'X = \begin{bmatrix} 12 & 60 \\ 60 & 360 \end{bmatrix} \quad X'Y = \begin{bmatrix} 120 \\ 800 \end{bmatrix} \quad Y'(I - P)Y = 20 \quad Y'(P - \frac{1}{n}J)Y = 250
\]
p.5.a. Compute \( \hat{\beta} \) and \( V \{ \hat{\beta} \} \)

p.5.b. Give a 95% Confidence Interval for \( \beta_i \)

p.5.c. Test \( H_0 : \beta_i = 0 \quad H_A : \beta_i \neq 0 \) at \( \alpha = 0.05 \) significance level.

Q.6. Write out \( \frac{SS_{\mu}}{\sigma^2} \) and \( \frac{SSE}{\sigma^2} \) as quadratic forms involving \( Y \). Obtain the sampling distributions for each quantity and show they are independent.

Q.7. Write \( e \) as a linear function of \( Y \), and use that to derive the mean vector and covariance matrix of \( e \). Are the residuals uncorrelated?

Q.8. For SLR in matrix form, derive the least squares estimate for \( \beta \)

Q.9. For SLR in matrix form, obtain \( SS_{\text{Model}} = \sum_{i=1}^{n} (\hat{Y}_i)^2 \) and \( SSE = \sum_{i=1}^{n} e_i^2 \) in matrix form (quadratic forms in \( Y \)). Obtain the distributions of the two sum of squares divided by \( \sigma^2 \) (be specific with regard to their family of distributions, degrees of freedom, and non-centrality parameters).

Q.10. For SLR in matrix form: Derive the Covariance of the vector of sample means and the vector of fitted values:

\[
\bar{Y} = \bar{Y}_n = \frac{1}{n} J_n Y \quad Y = X\beta = X(X'X)^{-1}X'Y = PY
\]

Q.11. Consider the simple linear regression model:

\[
Y_i = \beta_0 + \beta_1 (X_i - \bar{X}) + \epsilon_i \quad i = 1, \ldots, n \quad \epsilon_i \sim NID(0, \sigma^2)
\]

p.11.a. Give the corresponding \( X \) matrix \( Y \) vector, and \( \beta \) (symbolically):

p.11.b. Give the following matrices and vectors (symbolically): \( X'X \), \( (X'X)^{-1} \), \( X'Y \) \( \hat{\beta} \)
Q.12. Consider the MODEL Sum of Squares for Model 2. \(SS(\text{Model}) = \hat{Y}' \hat{Y} = Y'AY\)

p.12.a. Give the defining matrix \(A\) and show that it is idempotent.

p.12.b. Derive the degrees of freedom for \(SS(\text{Model})\)

p.12.c. Derive the non-centrality parameter for the non-central chi-square distribution of \(SS(\text{Model})/\sigma^2\)

p.12.d. Show that \(SS(\text{Model})/\sigma^2\) and \(SS(\text{Residual})/\sigma^2\) are independent (state \(SS(\text{Residual})\) as quadratic form)

Q.13. A simple linear regression was fit, relating the modulus of a tire (\(Y\)) to the amount of weeks (\(X\)) heated at 125\(^0\), with results given below:

<table>
<thead>
<tr>
<th>Weeks ((X))</th>
<th>Modulus ((Y))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2.3</td>
</tr>
<tr>
<td>1</td>
<td>4.2</td>
</tr>
<tr>
<td>2</td>
<td>5.2</td>
</tr>
<tr>
<td>4</td>
<td>5.9</td>
</tr>
<tr>
<td>6</td>
<td>6.3</td>
</tr>
<tr>
<td>15</td>
<td>7.2</td>
</tr>
</tbody>
</table>

p.13.a. For SLR in matrix form, obtain \(X\), \(Y\), \(X'X\), \((X'X)^{-1}\), and \(X'Y\)

p.13.b. Compute \(\hat{\beta}, \hat{Y}, e, MSE, V(\hat{\beta})\)

p.13.c. Compute a 95\% Confidence Interval for the change in the mean of modulus as weeks (\(X\)) increases by 1

Q.14. A simple regression model is fit, with 1 predictor and an intercept. Define the projection matrix as:
\[P = X(X'X)^{-1}X'.\]

p.14.a. Show that \(P\) is symmetric and idempotent. (Hint: \((X'X)^{-1}\) is symmetric)

p.14.b. What does \(\sum_{j=1}^{n} P_{ij}\) equal? Where \(P_{ij}\) is the element of \(P\) in the \(i^{th}\) row and \(j^{th}\) column

p.14.c. What does \(\sum_{j=1}^{n} P_{ij}^2\) equal?

p.14.d. What does \(\sum_{j=1}^{n} \left( P_{ij} - \overline{P_i} \right)^2\) equal?
Q.15. The total salaries (X, in millions of pounds) and the number of points earned (Y) for the n = 20 English Premier League teams in 1995/6 are used to fit a simple linear regression model. For this problem, we will treat this as a sample from a population of all possible league teams.

<table>
<thead>
<tr>
<th>Team</th>
<th>Int</th>
<th>WageK</th>
<th>Points(Y)</th>
<th>X'X</th>
<th>X'Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arsenal</td>
<td>1</td>
<td>10.1</td>
<td>63</td>
<td>20</td>
<td>170.9</td>
</tr>
<tr>
<td>Aston Villa</td>
<td>1</td>
<td>7.7</td>
<td>63</td>
<td>170.9</td>
<td>1745.15</td>
</tr>
<tr>
<td>Blackburn</td>
<td>1</td>
<td>10.8</td>
<td>61</td>
<td>170.9</td>
<td>1745.15</td>
</tr>
<tr>
<td>Bolton</td>
<td>1</td>
<td>3.3</td>
<td>29</td>
<td>170.9</td>
<td>1745.15</td>
</tr>
<tr>
<td>Chelsea</td>
<td>1</td>
<td>9.2</td>
<td>50</td>
<td>170.9</td>
<td>1745.15</td>
</tr>
<tr>
<td>Coventry</td>
<td>1</td>
<td>5.8</td>
<td>38</td>
<td>170.9</td>
<td>1745.15</td>
</tr>
<tr>
<td>Everton</td>
<td>1</td>
<td>10.1</td>
<td>61</td>
<td>170.9</td>
<td>1745.15</td>
</tr>
<tr>
<td>Leeds</td>
<td>1</td>
<td>10.1</td>
<td>43</td>
<td>170.9</td>
<td>1745.15</td>
</tr>
<tr>
<td>Liverpool</td>
<td>1</td>
<td>13.2</td>
<td>71</td>
<td>170.9</td>
<td>1745.15</td>
</tr>
<tr>
<td>Manchester City</td>
<td>1</td>
<td>6.4</td>
<td>38</td>
<td>170.9</td>
<td>1745.15</td>
</tr>
<tr>
<td>Manchester United</td>
<td>1</td>
<td>13.3</td>
<td>72</td>
<td>170.9</td>
<td>1745.15</td>
</tr>
<tr>
<td>Middlesbrough</td>
<td>1</td>
<td>6.5</td>
<td>43</td>
<td>170.9</td>
<td>1745.15</td>
</tr>
<tr>
<td>Newcastle</td>
<td>1</td>
<td>19.7</td>
<td>78</td>
<td>170.9</td>
<td>1745.15</td>
</tr>
<tr>
<td>Nottingham Forest</td>
<td>1</td>
<td>8.5</td>
<td>58</td>
<td>170.9</td>
<td>1745.15</td>
</tr>
<tr>
<td>Queens Park</td>
<td>1</td>
<td>5</td>
<td>33</td>
<td>170.9</td>
<td>1745.15</td>
</tr>
<tr>
<td>Sheffield</td>
<td>1</td>
<td>6.4</td>
<td>40</td>
<td>170.9</td>
<td>1745.15</td>
</tr>
<tr>
<td>Southampton</td>
<td>1</td>
<td>4.1</td>
<td>38</td>
<td>170.9</td>
<td>1745.15</td>
</tr>
<tr>
<td>Tottenham</td>
<td>1</td>
<td>9.8</td>
<td>61</td>
<td>170.9</td>
<td>1745.15</td>
</tr>
<tr>
<td>West Ham United</td>
<td>1</td>
<td>6.2</td>
<td>51</td>
<td>170.9</td>
<td>1745.15</td>
</tr>
<tr>
<td>Wimbledon</td>
<td>1</td>
<td>4.7</td>
<td>41</td>
<td>170.9</td>
<td>1745.15</td>
</tr>
</tbody>
</table>

p.15.a. Compute \( (X'X)^{-1} \) and \( \hat{\beta} \)

p.15.b. Compute the fitted value and residual for Arsenal.

p.15.c. Given \( \bar{Y} = 52.1 \) and \( \sum_{i=1}^{20} (Y_i - \bar{Y})^2 = 4367.8 \) Compute \( SSR \) and \( SSE \)

p.15.d. Obtain a 95% Confidence Interval for \( \beta_1 \)

Q.16. For the Analysis of Variance in SLR, with \( n \) observations and 1 predictor, complete the following parts.

p.16.a. Write the Regression and Residual sums of squares as quadratic forms.

p.16.b. Derive the distributions of \( SSR/\sigma^2 \) and \( SSE/\sigma^2 \)

p.16.c. Show that \( SSR/\sigma^2 \) and \( SSE/\sigma^2 \) are independent
Q.17. The following measurements were obtained at n=5 locations on the earth’s surface, where Y=measured gravity, and X= latitude. Consider fitting SLR, containing an intercept. Note this includes the fitted values and residuals from results of p.4.a, and makes use of both scalar model and matrix model.

<table>
<thead>
<tr>
<th>Obs#</th>
<th>X(Lat)</th>
<th>Y(Grav)</th>
<th>Y-hat</th>
<th>e</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
<td>1.10</td>
<td>1.08</td>
<td>0.02</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>1.60</td>
<td>1.54</td>
<td>0.06</td>
</tr>
<tr>
<td>3</td>
<td>40</td>
<td>1.90</td>
<td>2.00</td>
<td>-0.10</td>
</tr>
<tr>
<td>4</td>
<td>50</td>
<td>2.40</td>
<td>2.46</td>
<td>-0.06</td>
</tr>
<tr>
<td>5</td>
<td>60</td>
<td>3.00</td>
<td>2.92</td>
<td>0.08</td>
</tr>
</tbody>
</table>

p.17.a. Obtain the following matrices and vectors.

\[
\begin{array}{c|c|c|c|c}
\text{X'X} & & & \\
\hline
\text{X'Y} & & & \\
\hline
\text{INV(X'X)} & & & \\
\text{Beta-hat} & & & \\
\end{array}
\]

p.17.b. Compute the residual sum of squares, and give its degrees of freedom (based on scalar model).
p.17.c. Compute the regression sum of squares, and give its degrees of freedom (based on scalar model).
p.17.d. Conduct the F-test, testing \( H_0: \beta_1 = 0 \) vs \( H_A: \beta_1 \neq 0 \) at \( \alpha = 0.05 \) significance level.
p.17.d.i. Test Statistic: 

p.17.d.ii. Rejection Region:  

Q.18. In the matrix form of the simple linear regression model, the least squares estimator for \( \beta \) is  

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

where the elements of \( X \) are fixed constants in a controlled laboratory experiment.

p.18.a. Derive \( E\left\{ \hat{\beta} \right\} \)  \textit{Show all work}

p.18.b. Derive \( V\left\{ \hat{\beta} \right\} \)  \textit{Show all work}
Q.19. An experiment is conducted, relating weekly sales for a food delivery (Y) service to the amount of advertising (X) during the week. The results for a sample of n = 6 weeks are given below. Fit SLR in matrix form by filling in the following matrices.

<table>
<thead>
<tr>
<th>Week</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ad Spend (X)</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Sales (Y)</td>
<td>20</td>
<td>30</td>
<td>40</td>
<td>50</td>
<td>70</td>
<td>60</td>
</tr>
</tbody>
</table>

\[
X = \begin{bmatrix}
\text{Week 1} \\
\text{Week 2} \\
\text{Week 3} \\
\text{Week 4} \\
\text{Week 5} \\
\text{Week 6}
\end{bmatrix}, \quad Y = \begin{bmatrix}
\text{Sales 1} \\
\text{Sales 2} \\
\text{Sales 3} \\
\text{Sales 4} \\
\text{Sales 5} \\
\text{Sales 6}
\end{bmatrix}, \quad X'X = \begin{bmatrix}
\Sigma(X_1^2) & \Sigma(X_1X_2) & \Sigma(X_1X_3) & \Sigma(X_1X_4) & \Sigma(X_1X_5) & \Sigma(X_1X_6) \\
\Sigma(X_2X_1) & \Sigma(X_2^2) & \Sigma(X_2X_3) & \Sigma(X_2X_4) & \Sigma(X_2X_5) & \Sigma(X_2X_6) \\
\Sigma(X_3X_1) & \Sigma(X_3X_2) & \Sigma(X_3^2) & \Sigma(X_3X_4) & \Sigma(X_3X_5) & \Sigma(X_3X_6) \\
\Sigma(X_4X_1) & \Sigma(X_4X_2) & \Sigma(X_4X_3) & \Sigma(X_4^2) & \Sigma(X_4X_5) & \Sigma(X_4X_6) \\
\Sigma(X_5X_1) & \Sigma(X_5X_2) & \Sigma(X_5X_3) & \Sigma(X_5X_4) & \Sigma(X_5^2) & \Sigma(X_5X_6) \\
\Sigma(X_6X_1) & \Sigma(X_6X_2) & \Sigma(X_6X_3) & \Sigma(X_6X_4) & \Sigma(X_6X_5) & \Sigma(X_6^2)
\end{bmatrix}, \quad X'Y = \begin{bmatrix}
\Sigma(X_1Y_1) \\
\Sigma(X_2Y_2) \\
\Sigma(X_3Y_3) \\
\Sigma(X_4Y_4) \\
\Sigma(X_5Y_5) \\
\Sigma(X_6Y_6)
\end{bmatrix}
\]

\[
(X'X)^{-1} = \begin{bmatrix}
\frac{1}{\Sigma(X_1^2)} & \frac{-\Sigma(X_1X_2)}{\Sigma(X_1^2)\Sigma(X_2^2) - \Sigma(X_1X_2)^2} & \frac{-\Sigma(X_1X_3)}{\Sigma(X_1^2)\Sigma(X_3^2) - \Sigma(X_1X_3)^2} & \frac{-\Sigma(X_1X_4)}{\Sigma(X_1^2)\Sigma(X_4^2) - \Sigma(X_1X_4)^2} & \frac{-\Sigma(X_1X_5)}{\Sigma(X_1^2)\Sigma(X_5^2) - \Sigma(X_1X_5)^2} & \frac{-\Sigma(X_1X_6)}{\Sigma(X_1^2)\Sigma(X_6^2) - \Sigma(X_1X_6)^2}
\end{bmatrix}, \quad \hat{\beta} = (X'X)^{-1}X'Y
\]

\[
\hat{Y} = \hat{\beta}X, \quad e = Y - \hat{Y}
\]

\[
SSE = e'e = \frac{\sum(Y_i - \hat{Y}_i)^2}{n}
\]

Q.20. For the simple regression model, with an intercept term, complete the following parts

p.20.a. \( Y = \hat{Y} + e \), \( \hat{Y} = X\hat{\beta} \), \( \bar{Y} = \frac{1}{n}\sum Y \) prove that \( (Y - \bar{Y})'(Y - \bar{Y}) = (\hat{Y} - \bar{Y})'(\hat{Y} - \bar{Y}) + e'e \)

p.20.b. Derive the sampling distributions of \( \hat{Y} - \bar{Y} \) and \( e \)

Q.21. Based on Model 2, with \( \hat{\beta} = (X'X)^{-1}X'Y \):

p.21.a. Derive the sampling distributions of the vectors \( \hat{Y}, e, \bar{Y} \)

p.21.b. Derive the sampling distributions of \( \frac{SSE}{\sigma^2} \) and \( \frac{SSR}{\sigma^2} \) and show they are independent.

p.21.c. Give the sampling distribution of \( F = \frac{MSR}{MSE} \) under \( H_0: \beta_1 = 0. \)
Q.22. Consider regression through the origin in matrix form where $1$ is an $n \times 1$ vector of $1$.

$$
\begin{bmatrix}
Y_1 \\
\vdots \\
Y_n
\end{bmatrix} =
\begin{bmatrix}
1 \\
\vdots \\
1
\end{bmatrix} X 
\begin{bmatrix}
\beta_1 \\
\vdots \\
\beta_n
\end{bmatrix} + \epsilon
\quad E\{\epsilon\} = 0
\quad V\{\epsilon\} = \sigma^2 I
\quad \hat{\beta} = (X'X)^{-1} X'Y
\quad \beta = (1'X)^{-1} 1'Y
$$

Derive the means, variances, and covariance of

$$
\hat{\beta} \quad \text{and} \quad \tilde{\beta} \quad \text{where} \quad \text{COV}\{AY, BY\} = E\{(AY - A\mu_Y)(BY - B\mu_Y)^T\}
$$

Q.23. A simple linear regression (with an intercept) is fit, relating $Y$ to $X$. The data are given below.

<table>
<thead>
<tr>
<th>$X$</th>
<th>0</th>
<th>0</th>
<th>2</th>
<th>2</th>
<th>4</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Y$</td>
<td>12</td>
<td>8</td>
<td>14</td>
<td>16</td>
<td>23</td>
<td>17</td>
</tr>
</tbody>
</table>

p.23.a. Give the following matrices and vectors. $X$, $Y$, $X'X$, $X'Y$, $Y'Y$, $(X'X)^{-1}$, $\hat{\beta}$, $\hat{\mu}_Y$, $e$

p.23.b. Compute the following sums of square: SS Model, SS$\mu$, SS Regression, and SS Error

Q.24. Based on Model 2, with $\hat{\beta} = (X'X)^{-1} X'Y$:

p.24.a. Derive the sampling distributions of the vectors $\hat{Y}$, $e$, $\bar{Y}$, $Y - \bar{Y}$ Show all work

p.24.b. Derive the sampling distributions of $\frac{TSS}{\sigma^2}$ and $\frac{SS\mu}{\sigma^2}$ where $SS\mu = n\bar{Y}^2 = Y'A\mu_Y$ and show they are independent. Show all work

Q.25. A simple linear regression model is fit, where $n=143$ cats weighing over 2 kilograms were observed. The response variable was heart weight ($Y$, in grams) and the predictor was body weight ($X$, in kilograms). The estimated regression coefficient vector and its variance covariance matrix are given below.

$$
\hat{\beta} =
\begin{bmatrix}
0.12 \\
3.85
\end{bmatrix}
\quad \text{V} \{\hat{\beta}\} =
\begin{bmatrix}
0.4489 & -0.1561 \\
-0.1561 & 0.0576
\end{bmatrix}
\quad \bar{X} = 2.71
$$

p.25.a. Obtain the predicted heart weight for a cat weighing 3.0 kilograms.

p.25.b. Compute a 95% Confidence Interval for the mean heart weight for all cats weighing 3 kilograms.
Q.26. A simple linear regression model was fit, relating the number of airplane tires consumed (Y) to the number of landings (X, in 100s) at an airfield over a series of periods. Based on Model 2, the following results were obtained.

<table>
<thead>
<tr>
<th>X'X</th>
<th>X'Y</th>
<th>Y'Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>95.91</td>
<td>1051</td>
</tr>
<tr>
<td>95.91</td>
<td>502.7151</td>
<td>5439.48</td>
</tr>
<tr>
<td>INV(X'X)</td>
<td>Beta-hat</td>
<td></td>
</tr>
<tr>
<td>0.58758</td>
<td>-0.11210</td>
<td>7.7761</td>
</tr>
<tr>
<td>-0.11210</td>
<td>0.02338</td>
<td>9.3366</td>
</tr>
</tbody>
</table>

p.26.a. How many periods were observed by the researchers? ___________
p.26.b. How many total aircraft landings were there during the study? ________________
p.26.c. How many tires were consumed over the study? ________________
p.26.d. Compute: \( Y'Y \quad Y'PY \quad Y' \frac{1}{n} JY \)
p.26.e. Compute \( SSE = \sum_{i=1}^{n} \left( Y_i - \hat{Y}_i \right)^2 \) and \( SSR = \sum_{i=1}^{n} \left( \hat{Y}_i - \bar{Y} \right)^2 \)
p.26.f. Compute \( \hat{\beta} \)

Q.27. A study in Beijing, China related heights (Y, cm) to mean foot length (X, cm) in a sample of \( n = 174 \) male college students. The sample means, standard deviations and correlations are given below. Complete the following table for the simple linear regression relating Height (Y) to mean foot length (X).

\[
\bar{X} = 24.93 \quad \bar{Y} = 177.65 \quad s_x = \sqrt{\frac{\sum_{i=1}^{n} (X_i - \bar{X})^2}{n-1}} = 0.903 \quad s_y = 4.810 \quad r_{xy} = 0.483
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