Generalized Inference in Linear Regression Models

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GENERALIZED INFERENCE IN LINEAR REGRESSION MODELS

by

Quazi Imad Uddin Ibrahim

A Thesis
Submitted to the Faculty of Graduate Studies through the Department of Mathematics and Statistics in Partial Fulfillment of the Requirements for the Degree of Master of Science at the University of Windsor

Windsor, Ontario, Canada

2009

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Abstract

In this thesis, we consider inference problems in linear regression under both homoscedasticity and heteroscedasticity of the error noise. Namely, we construct generalized confidence regions and generalized confidence intervals for regression coefficients of linear regression models. Regressor variables are considered non-stochastic. Independent normal errors with zero mean and constant or varying dispersion are considered. The regression data from two different regimes are considered. In testing the equality of the regression coefficients in the two regimes under heteroscedasticity, we develop the generalized pivotal quantities of their differences and the generalized p-values. Generalized methods of inference are especially useful in multiparameter cases where nontrivial tests are difficult to obtain. We propose generalized test variables and generalized p-values to test the equality of the sets of regression coefficients of the two regimes. The test can be applied efficiently for all sample sizes and for homoscedastic as well as heteroscedastic cases. The simulation study shows that the proposed method preserves the nominal significance level and maintain satisfactory power under heteroscedasticity, and for small and moderate sample sizes. We also construct the generalized confidence region for the difference of the two sets of regression coefficients. When the regression coefficients remained the same for the two regimes under heteroscedasticity, we propose generalized confidence regions and generalized confidence intervals for the regression parameters.

We applied the proposed method on the community health study data of Sarnia in 2005 and the US gasoline consumption data before and after the 1973 oil crisis. The analysis results show that, for both data sets, the regime change is statistically significant at 5% level.
Dedication

This thesis is dedicated to my family. I am grateful to my family for their continuous support and encouragement. I remember their love, affection and inspiration throughout my life.
All praises are due to almighty Allah. I express my sacred gratitude to the omnipotent and omniscient Allah, Who gave us the wisdom of creation. Without His blessings this task could not have ended.

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1 Introduction
   1.1 Literature review ............................................. 1
   1.2 Objective .................................................. 6

2 Generalized Confidence Intervals for Simple Linear Regression Parameters
   2.1 Error terms are normal random variables
       with zero mean and constant variance ........................ 8
       2.1.1 Generalized confidence interval (GCI) for $\beta_1$ ..... 9
       2.1.2 GCI for $\beta_0$ ......................................... 10
       2.1.3 GCI for dispersion parameter ............................ 11
       2.1.4 GCI for expected response for given X ................. 12
   2.2 Error distribution is normal with zero mean and varying dispersion . 13
CONTENTS

2.3 Heteroscedasticity in two different regimes ........................................... 15
   2.3.1 GCI for $\beta_0$ and $\beta_1$ when $\sigma^2_1$ and $\sigma^2_2$ are known .......... 16
   2.3.2 GCI for $\beta_0$ and $\beta_1$ when $\sigma^2_1$ and $\sigma^2_2$ are unknown ........ 17
2.4 Testing equality of corresponding regression coefficients under het-
   eroscedasticity .................................................................................. 19

3 Generalized Inference for Multiple Linear Regression Parameters 23
   3.1 Error terms are normal random variables with zero mean and constant
       variance ................................................................................... 25
      3.1.1 Generalized confidence region (GCR) for $\beta$ ................................. 25
      3.1.2 Generalized confidence interval (GCI) for $\beta_i$ ............................... 27
      3.1.3 GCI for dispersion parameter .................................................... 29
   3.2 Error distribution is normal with zero mean and varying dispersion . 29
   3.3 Heteroscedasticity in two different regimes ................................. 30
      3.3.1 GCR and GCI for regression coefficients when $\sigma^2_1$ and $\sigma^2_2$ are
          known ............................................................................... 30
      3.3.2 GCR and GCI for regression coefficients when $\sigma^2_1$ and $\sigma^2_2$ are
          unknown ............................................................................... 31
   3.4 Testing equality of corresponding regression coefficients under het-
       eroscedasticity ........................................................................ 33

4 Simulation Study 37
   4.1 Simulation result for simple linear regression model ......................... 37
   4.2 Simulation result for multiple linear regression model ....................... 56
   4.3 Conclusion .................................................................................. 61

5 Application of Proposed Generalized Methods on Real Data 62
   5.1 Is air pollution in Sarnia causing respiratory problems among adults? 62
      5.1.1 Description of the data .......................................................... 63
      5.1.2 Analysis results .................................................................. 63
      5.1.3 Conclusion ......................................................................... 65
<table>
<thead>
<tr>
<th>CONTENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.2  Impact of gasoline price on total US gasoline consumption before and after 1973 oil crisis</td>
</tr>
<tr>
<td>5.2.1 Description of the data</td>
</tr>
<tr>
<td>5.2.2 Analysis results</td>
</tr>
<tr>
<td>5.2.3 Conclusion</td>
</tr>
<tr>
<td>6  Conclusion and Future Research</td>
</tr>
<tr>
<td>Appendix</td>
</tr>
<tr>
<td>A</td>
</tr>
<tr>
<td>A.1 Distributions of the estimators of the error variance in linear regression</td>
</tr>
<tr>
<td>A.2 Ordinary least squares estimators $\hat{\beta}$ is independent of error mean square</td>
</tr>
<tr>
<td>A.3 U and V are independent</td>
</tr>
<tr>
<td>Bibliography</td>
</tr>
<tr>
<td>Vita Auctoris</td>
</tr>
</tbody>
</table>
List of Tables

4.1 Fixed X values for different sample sizes ........................................ 43
4.2 Empirical confidence levels for 95% generalized confidence intervals of
the classical linear regression parameters ........................................... 44
4.3 Observed confidence levels for 95% generalized confidence intervals of
the classical linear regression parameters in the case of heteroscedasticity 45
4.4 Observed confidence levels for 95% generalized confidence intervals of
the simple linear regression coefficients when error variances $\sigma_1^2 = 4$
and $\sigma_2^2 = 9$ of the two regimes are assumed known ....................... 46
4.5 Observed confidence levels for 95% generalized confidence intervals of
the simple linear regression coefficients when error variances $\sigma_1^2 = 4$
and $\sigma_2^2 = 9$ of the two regimes are assumed unknown .................... 47
4.6 Observed significance levels of the generalized and classical test in test-
ing the equality of the regression coefficients in homoscedastic case
($\sigma_1^2 = \sigma_2^2 = 4$) ........................................................................ 48
4.7 Observed significance levels of the generalized and classical tests in test-
ing the equality of the regression coefficients in heteroscedastic cases
at 0.05 level of significance ................................................................. 49
4.8 Observed significance levels of the generalized test and the test based
on approximate $t$ distribution in testing the equality of the regression
coefficients in heteroscedastic cases at 0.05 level of significance ......... 50
4.9 Power of the tests in testing the equality of the slope parameters \((\beta_{11} = \beta_{21} = 2)\) in the two regimes with heteroscedasticity at 0.05 level of significance .................................................. 51

4.10 Size and power of the generalized test and the test based on approximate \(t\) in testing the equality of the slope parameters \((\beta_{11} - \beta_{21} = 0)\) in the two regimes of sample sizes \(n_1 = 15\) and \(n_2 = 5\) in heteroscedastic cases at 0.05 level of significance ............................................ 52

4.11 Fixed X values for different sample sizes ............................................. 58

4.12 Observed significance levels of the generalized test (GT) in testing the equality of the two sets of regression coefficients in the two regimes with heteroscedasticity at 0.05 level of significance ................. 59

4.13 Power of the generalized test (GT) in testing the equality of the two sets of regression coefficients in the two regimes of sample sizes \(n_1 = 15\) and \(n_2 = 5\) with heteroscedasticity at 0.05 level of significance ....... 60

5.1 Analysis of variance for the linear regression model of mean number of respiratory problems on years of living in Sarnia .............................. 69

5.2 Estimates of the parameters for the linear regression model of mean number of respiratory problems on years of living in Sarnia ............... 69

5.3 the Correlation coefficient between years of living in Sarnia and the mean number of respiratory problems by region ................................. 70

5.4 Estimates of the parameters for the linear regression model of mean number of respiratory problems on years of living in Sarnia by region .... 70

5.5 The 95 percent Generalized confidence intervals for the difference of the regression coefficients in regions N7S and N7T ................................. 70

5.6 Analysis of variance for the linear regression model of mean number of respiratory problems on years of living in Sarnia and age of respondents 71

5.7 Estimates of the parameters for the linear regression model of mean number of respiratory problems on years of living in Sarnia and age of respondents .......................................................... 71
LIST OF TABLES

5.8 Estimates of the parameters for the linear regression model of the total US gasoline consumption on price index for gasoline and price index for used cars during 1960 and 1995 ........................................ 79
5.9 Collinearity diagnostics for the linear regression model of the total US gasoline consumption on price index for gasoline (PIG) and price index for used cars (PUC) during 1960 and 1995 ........................................ 79
5.10 Estimates of the parameters for the linear regression model of the total US gasoline consumption on price index for gasoline (PIG) and price index for used cars (PUC) before and after the oil crisis in 1973 . . . . 80
5.11 The Generalized confidence intervals for the difference of the corresponding regression coefficients of two regimes each with confidence coefficient 0.98 ........................................ 80
List of Figures

4.1 Power of the generalized test at 0.05 level of significance in testing the equality of the slope parameters ($\beta_{11} = \beta_{12}$) in the two regimes with severe heteroscedasticity $\sigma^2_1 = 4$ and $\sigma^2_2 = 25$ for different sample sizes 53

4.2 Power of the classical test based on the equal variance assumption in testing the equality of the slope parameters ($\beta_{11} = \beta_{12}$) in the two regimes with severe heteroscedasticity $\sigma^2_1 = 4$ and $\sigma^2_2 = 25$ for different sample sizes at 0.05 level of significance 54

4.3 Power of the generalized and classical tests in testing the equality of the slope parameters ($\beta_{11} = \beta_{12}$) in the two regimes with severe heteroscedasticity $\sigma^2_1 = 4$ and $\sigma^2_2 = 25$ for overall sample size 20 ($n_1 = 8$ and $n_2 = 12$) at 0.05 level of significance 55

5.1 The scatter plot of the years of living in Sarnia and the number of respiratory problems 66

5.2 The scatter plot of the years of living and the mean number of respiratory problems for the five regions in Sarnia 67

5.3 The scatter plot of the years of living and the mean number of respiratory problems for the five regions in Sarnia after excluding groups with no respiratory problems 68

5.4 The plot of the consumption of gasoline by years 76

5.5 The plot of the price index for gasoline by years 77

5.6 The scatter plot of the price and consumption of gasoline before and after the oil crisis 78
Chapter 1

Introduction

1.1 Literature review

In estimation, we often infer the true value of the parameter or a function of the parameter is contained in an interval with certain confidence. These intervals are called confidence intervals. To define confidence intervals consider a random sample \(Y = (Y_1, Y_2, \ldots, Y_n)\) from a probability density function (pdf) or a probability mass function (pmf) \(f(y|\theta)\) where \(\theta\) is an unknown parameter. Suppose \(T_1(Y)\) and \(T_2(Y)\) are two statistics such that

\[
Pr[T_1(Y) \leq \theta \leq T_2(Y)] = \gamma, \quad \gamma \in (0, 1).
\]

If the realized values of \(T_1(Y)\) and \(T_2(Y)\) are \(a\) and \(b\) respectively, \([a, b]\) is called a 100\(\gamma\) percent confidence interval for \(\theta\). Here \(\gamma\) is called the confidence coefficient. Typical values of \(\gamma\) are 0.9, 0.95 and 0.99. One method of constructing confidence interval is to use a pivotal quantity.

**Definition (Pivotal quantity):** Let \(Y = (Y_1, Y_2, \ldots, Y_n)\) be a random sample from a probability density function (pdf) or a probability mass function (pmf) \(f(y|\theta)\) where \(\theta\) is an unknown parameter and \(Q = g(Y, \theta)\) is a function of \(Y\) and \(\theta\). If \(Q\) has a probability distribution independent of any unknown parameters, it is called a pivotal quantity.
Thus for a fixed $\gamma$, there exist real numbers $q_1$ and $q_2$ ($q_1 < q_2$) such that

$$Pr[q_1 \leq g(Y, \theta) \leq q_2] = \gamma, \quad \gamma \in (0, 1).$$

If $q_1 \leq g(Y, \theta) \leq q_2 \iff T_1(Y) \leq \theta \leq T_2(Y)$ where $T_1(Y)$ and $T_2(Y)$ are functions of sample only, the random interval $[T_1(Y), T_2(Y)]$ is called a 100$\gamma$ percent confidence interval for $\theta$. For an observed sample point $y = (y_1, y_2, \ldots, y_n)$, $[T_1(y), T_2(y)]$ is also called a 100$\gamma$ percent confidence interval for $\theta$.

In complex situations involving nuisance parameters, often the uniformly most accurate confidence intervals are unavailable. For instance, the uniformly most accurate unbiased confidence intervals for the difference in means of two independent normal populations do not exist unless the population variances are assumed equal. When the variances are heterogeneous, this problem is known as the Behrens-Fisher problem (Welch, 1938). To overcome this problem, Weerahandi (1993) introduced the concept of generalized pivotal quantity and generalized confidence interval.

**Definition (Generalized pivotal quantity):** Let $Y = (Y_1, Y_2, \ldots, Y_n)$ be a random sample from a distribution involving parameters $\theta$ and $\delta$. We are interested in constructing a confidence interval for $\theta$. Let $y = (y_1, y_2, \ldots, y_n)$ be the observed sample. The generalized pivotal quantity, denoted by $R(Y, y, \theta, \delta)$, has the following three properties:

1. $R$ is a function of $Y$, $y$, $\theta$ and $\delta$,
2. the distribution of $R$ is independent of $\theta$ and $\delta$ and
3. $R(y, y, \theta, \delta)$ does not depend on $\delta$.

In this thesis, we consider a more specific generalized pivotal function that satisfies $R(y, y, \theta, \delta) = \theta$. Accordingly, a 100$(1 - \alpha)$ percent generalized confidence interval for $\theta$ is $[R_{\alpha/2}, R_{1-\alpha/2}]$ where $R_{\alpha/2}$ and $R_{1-\alpha/2}$ are the $100(\alpha/2)^{th}$ and $100(1 - \alpha/2)^{th}$ percentiles of $R(Y, y, \theta, \delta)$. It is noticed that generalized confidence intervals can be constructed for small as well as for large samples.
In passing, recall the duality between the uniformly most accurate confidence interval and the uniformly most powerful (UMP) test. Thus, for the above mentioned problem where classical inference does not provide an optimal (small sample) confidence interval, the UMP unbiased test does not exist too. Tsui and Weerahandi (1989) introduced generalized test variables and generalized p-values to deal with this problem.

**Definition (Generalized test variable):** Let \( Y = (Y_1, Y_2, \ldots, Y_n) \) be a random sample from a distribution involving parameters \( \theta \) and \( \delta \). We are interested in testing the hypothesis
\[
H_0 : \theta = \theta_0 \text{ against } H_1 : \theta \neq \theta_0.
\]
Let \( y = (y_1, y_2, \ldots, y_n) \) be the observed sample. The generalized test variable, denoted by \( T(Y, y, \theta, \delta) \), is a function of \( (Y, y, \theta, \delta) \) that satisfies the following requirements:

1. For given \( y \) and \( (\theta_0, \delta) \) the distribution of \( T \) is independent of the nuisance parameter \( \delta \).
2. \( t = T(y, y, \theta, \delta) \) does not depend on any unknown parameters.
3. For given \( y \) and \( \delta \), \( P(T \geq t) \) is stochastically monotone in \( \theta \), i.e. stochastically increasing or decreasing in \( \theta \).

In general, for a given \( y \) and \( \delta \) we can take
\[
T(Y, y, \theta, \delta) = R(Y, y, \theta, \delta) - \theta
\]
and one can verify that, the distribution of \( T \) for given \( y \) and \( \delta \) is stochastically monotone in \( \theta \). In this case the generalized p-value for testing the hypothesis is
\[
P = 2 \min \left\{ \sup_{\theta = \theta_0} P(T \geq t), \sup_{\theta = \theta_0} P(T \leq t) \right\}
= 2 \min \left\{ \sup_{\theta = \theta_0} P(R \geq \theta), \sup_{\theta = \theta_0} P(R \leq \theta) \right\}
= 2 \min \{P(R \geq \theta_0), P(R \leq \theta_0)\}.
\]
In the same setting, if \( T(Y, y, \theta, \delta) \) satisfies the following conditions, it can be considered as a generalized test variable too (Gamage et al; 2004):
1. The distribution of $T(Y, y, \theta_0, \delta)$ is free of the nuisance parameter $\delta$.

2. $t = T(y, y, \theta_0, \delta)$ is free of $\delta$.

3. $P(T \geq t)$ is nondecreasing in $\theta$ for fixed $y$ and $\delta$.

McNally, Iyer and Mathew (2003) used the generalized test variables and the generalized p-values to test population and individual bioequivalence. They showed that these tests perform better than confidence interval methods and have superior power for assessing population bioequivalence.

Lin and Lee (2004) constructed a generalized pivotal quantity to estimate the common mean of several normal populations when the variances are unknown and unequal. The proposed generalized pivotal quantity was based on the best linear unbiased estimator of the common mean.

Gamage, Mathew and Weerahandi (2004) developed a procedure based on generalized p-values to test the equality of the mean vectors of two multivariate normal populations with unequal covariance matrix. They showed the type I error probability of their generalized p-value test did not exceed the nominal level. They constructed a generalized confidence region for the difference between the mean vectors. A solution of the heteroscedastic MANOVA problem using generalized p-value was also given.

Factors that influence the gun accuracy of an M1 series tank are of considerable interest in US army. One of the factors is gun tubes. Mathew and Webb (2005) developed generalized confidence intervals and generalized test variable to compare variability among two types of gun tubes (new tubes and control tubes). They considered mixed models for their generalized inference.

Hannig, Iyer and Patterson (2006) proposed fiducial generalized pivotal quantities as a subclass of generalized pivotal quantities. They showed that generalized confidence intervals constructed based on fiducial generalized pivotal quantities have asymptotically correct frequentist coverage. They found that the subfamily of fiducial generalized pivots has a close connection with fiducial inference proposed by R.
A. Fisher.

In Metrology, a measurand is based on a sequence of measurements each with type-A and type-B errors. The measurements may come from a single experiment or several separate experiments. Wang and Iyer (2006) proposed a generalized confidence interval for a measurand based on the two measurement models with different sets of assumptions on type-B errors.

Krishnamoorthy, Mathew and Ramachandran (2006) constructed generalized p-values and generalized confidence intervals to test and compute confidence interval for the mean of a lognormal distribution. They assessed occupational exposure using the lognormal mean. They showed that their proposed methods are easy to implement and applicable to small sample sizes. They extended their procedures to compare two lognormal means and to infer a lognormal variance.

Krishnamoorthy, Mathew and Ramachandran (2007) developed generalized pivotal quantities (GPQs) for the overall mean and the variance components for one-way random effects model. The GPQs were then used to construct tolerance limits in the one-way random effects model and to construct upper confidence limits for the exceedance probabilities of occupational exposure limit.

Bebu and Mathew (2007) proposed a generalized confidence interval for the ratio of the means of a bivariate log-normal distribution. They also suggested the same approach to obtain a confidence interval for the ratio of the variances. Simulated coverage probabilities of the proposed generalized confidence intervals were found satisfactory irrespective of the sample size. The power of the tests based on the GPQs were also found satisfactory.

Li, Xu and Li (2007) proposed a method of constructing generalized p-value via the fiducial inference. They discussed the properties of the power of the generalized test. They illustrated their methods for the two-parameter exponential distribution and unbalanced two-fold nested design.
1.2 Objective

Our objective is to find generalized confidence intervals for regression coefficients, dispersion parameters and the expected response for simple and multiple linear regression models with non-stochastic explanatory variables but under different assumptions of the error distribution:

(i) Error distribution is normal with zero mean and constant variance.

(ii) Error distribution is normal with zero mean and varying dispersion.

(iii) Heteroscedasticity in two different regimes.

With the same assumptions, we construct generalized confidence regions for multiple linear regression parameters. Also, for testing the equality of corresponding regression coefficients in two different regimes with heteroscedasticity, we develop generalized test variables, confidence regions, confidence intervals and p-values.
Chapter 2

Generalized Confidence Intervals for Simple Linear Regression Parameters

In this chapter we construct generalized confidence intervals for simple linear regression parameters under different scenarios. Consider a simple linear regression model of the form:

\[ Y_i = \beta_0 + \beta_1 X_i + \varepsilon_i, \quad i = 1, 2, ..., n, \]  

(2.1)

where \( Y \) is the response variable, \( X \) is the explanatory variable, \( \varepsilon \) is the random error term, and \( \beta_0 \) and \( \beta_1 \) are the regression coefficients. The regressor \( X \) is considered fixed throughout this chapter. In section 2.1, we assume independent normal errors with zero mean and constant variance. Based on this assumption we develop generalized pivotal quantities for the regression coefficients, dispersion parameter and expected response for a given value of \( X \) and then obtain their generalized confidence intervals. In section 2.2, errors are considered independently normally distributed with zero mean and varying dispersion, i.e. \( \varepsilon_i \sim N(0, \sigma_i^2) \). In particular, we take \( \sigma_i^2 = \sigma^2 X_i^2 \), where \( \sigma \) is constant (Dougherty; 1992). We construct generalized pivotal quantities for \( \beta_0 \), \( \beta_1 \) and \( \sigma^2 \). The notion of regimes is introduced in section 2.3. Regimes can be different time periods, different regions etc. We consider data from two regimes.
Chapter 2. Generalized Confidence Intervals for Simple Linear Regression Parameters

We assume the regression coefficients remain the same for the two regimes. The dispersion in error terms are assumed the same within the regime but different between regimes. We propose generalized pivotal quantities for the regression parameters in such case. In section 2.4, we test the equality of the corresponding regression coefficients of the two regimes. When the regimes’ error variances are different, it becomes a Behrens-Fisher problem problem in regression setting. We propose generalized pivotal quantities for the difference of the corresponding regression coefficients. The generalized p-values for testing the equality of corresponding slopes and intercepts of two regimes are then given.

2.1 Error terms are normal random variables with zero mean and constant variance

Suppose the error terms are iid normal with zero mean and constant variance $\sigma^2$. The maximum likelihood estimators for $\beta_0$, $\beta_1$ and $\sigma^2$ are $b_0 = \bar{Y} - b_1 \bar{X}$, $b_1 = \frac{\sum(X_i - \bar{X})Y_i}{\sum(X_i - \bar{X})^2}$ and $S_Y^2 = \frac{\sum(Y_i - \hat{Y}_i)^2}{n}$, respectively, where $\bar{X} = \frac{\sum X_i}{n}$, $\bar{Y} = \frac{\sum Y_i}{n}$ and $\hat{Y}_i = b_0 + b_1 X_i$.

Interval estimation will be based on these maximum likelihood estimators. The estimator $b = (b_0, b_1)'$ follows a bivariate normal distribution as

$$
\begin{pmatrix} b_0 \\ b_1 \end{pmatrix} \sim N_2 \left( \begin{pmatrix} \beta_0 \\ \beta_1 \end{pmatrix}, \sigma^2 \begin{pmatrix} 1/n + \frac{\bar{X}^2}{\sum (X_i - \bar{X})^2} & -\bar{X} \\ -\bar{X} & \frac{1}{\sum (X_i - \bar{X})^2} \end{pmatrix} \right),
$$

and $S_Y^2$ follows a chi-square distribution as

$$
\frac{nS_Y^2}{\sigma^2} \sim \chi^2_{n-2} \text{ (see Appendix A.1)}.
$$

Also, $b_0$ and $b_1$ are independent of $S_Y^2$ (see Appendix A.2).
2.1.1 Generalized confidence interval (GCI) for $\beta_1$

Denote generalized pivotal quantity (GPQ) for $\beta_1$ by $R_{\beta_1}$. We define

$$R_{\beta_1} = b_1 - \frac{b_1 - \beta_1}{\sigma} \sqrt{\sum (X_i - \bar{X})^2} \times \frac{\sigma}{\sqrt{\sum (X_i - \bar{X})^2}} \times \frac{s_y}{S_Y} = b_1 - \frac{b_1 - \beta_1}{\sqrt{\sum (X_i - \bar{X})^2}} \times \frac{1}{\sqrt{n}} \times \frac{S_Y^2}{\sigma^2} \times \frac{s_y}{\sqrt{\sum (X_i - \bar{X})^2}},$$

where $s_y$ is the observed value of $S_Y$. Here, $\frac{b_1 - \beta_1}{\sqrt{\sum (X_i - \bar{X})^2}} \sim N(0, 1)$ and $\frac{nS_Y^2}{\sigma^2} \sim \chi^2_{n-2}$. Further, they are independent as $b_1$ and $S_Y^2$ are independent.

Therefore,

$$R_{\beta_1} = b_1 - T_{n-2} \times \frac{\sqrt{n/(n-2)}s_y}{\sqrt{\sum (X_i - \bar{X})^2}},$$

(2.2)

where $T_{n-2}$ has a $t$-distribution with $n - 2$ degrees of freedom. From equation (2.2), the distribution of $R_{\beta_1}$ is independent of any unknown parameters. Also, the observed value of $R_{\beta_1}$ is $\beta_1$.

To construct a $100(1 - \gamma)$ percent GCI for $\beta_1$, we set

$$Pr(R_{\beta_1} < c) = 1 - \gamma/2.$$ 

This implies that

$$Pr \left( b_1 - T_{n-2} \times \frac{\sqrt{n/(n-2)}s_y}{\sqrt{\sum (X_i - \bar{X})^2}} < c \right) = 1 - \gamma/2.$$ 

Therefore,

$$Pr \left( T_{n-2} > \frac{\sqrt{\sum (X_i - \bar{X})^2}}{(\sqrt{n/(n-2)})s_y}(b_1 - c) \right) = 1 - \gamma/2.$$ 

Suppose $t_{n-2, \gamma/2}$ is the $100(1 - \gamma/2)^{th}$ percentile of $T_{n-2}$, then we get

$$\frac{\sqrt{\sum (X_i - \bar{X})^2}}{(\sqrt{n/(n-2)})s_y}(b_1 - c) = -t_{n-2, \gamma/2}.$$
Hence,

\[ c = b_1 + t_{n-2,\gamma/2} \cdot \frac{\left( \sqrt{n/(n-2)} \right) s_y}{\sqrt{\sum (X_i - \bar{X})^2}}. \]

Again, let

\[ Pr(R_{\beta_1} < d) = \gamma/2. \]

This implies that

\[ Pr \left( b_1 - T_{n-2} \cdot \frac{\left( \sqrt{n/(n-2)} \right) s_y}{\sqrt{\sum (X_i - \bar{X})^2}} < d \right) = \gamma/2, \]

or,

\[ Pr \left( T_{n-2} > \frac{\sqrt{\sum (X_i - \bar{X})^2}}{\left( \sqrt{n/(n-2)} \right) s_y} \cdot (b_1 - d) \right) = \gamma/2. \]

From the t-table we have \( Pr(T_{n-2} > t_{n-2,\gamma/2}) = \gamma/2. \) Then,

\[ \frac{\sqrt{\sum (X_i - \bar{X})^2}}{\left( \sqrt{n/(n-2)} \right) s_y} \cdot (b_1 - d) = t_{n-2,\gamma/2}. \]

Therefore,

\[ d = b_1 - t_{n-2,\gamma/2} \cdot \frac{\left( \sqrt{n/(n-2)} \right) s_y}{\sqrt{\sum (X_i - \bar{X})^2}}. \]

Thus, the 100(1 - \( \gamma \)) percent GCI for \( \beta_1 \) is

\[ [d, c] = \left[ b_1 - t_{n-2,\gamma/2} \cdot \frac{\left( \sqrt{n/(n-2)} \right) s_y}{\sqrt{\sum (X_i - \bar{X})^2}}, b_1 + t_{n-2,\gamma/2} \cdot \frac{\left( \sqrt{n/(n-2)} \right) s_y}{\sqrt{\sum (X_i - \bar{X})^2}} \right]. \]

2.1.2 GCI for \( \beta_0 \)

The GPQ for \( \beta_0 \) is

\[ R_{\beta_0} = b_0 - \frac{b_0 - \beta_0}{\sigma \sqrt{1/n + \bar{X}^2/\sum (X_i - \bar{X})^2}} \times \sigma \sqrt{1/n + \bar{X}^2/\sum (X_i - \bar{X})^2} \times \frac{s_y}{S_Y}, \quad (2.3) \]
then,
\[ R_{\beta_0} = b_0 - Z \sqrt{\frac{S^2 Y}{\sigma^2}} \times s_y \sqrt{\frac{1}{n} + \bar{X}^2 / \sum (X_i - \bar{X})^2} \]
with \( Z \sim N(0, 1) \).

Hence,
\[ R_{\beta_0} = b_0 - T_{n-2} \sqrt{\frac{n}{n-2}} s_y^2 (1/n + \bar{X}^2 / \sum (X_i - \bar{X})^2) \]
whose distribution is independent of any unknown parameters. Again, from (2.3) \( R_{\beta_0} = \beta_0 \) for observed value \((X, s_y^2)\). As in the case of generalized estimation of \( \beta_1 \), a similar set of operations and inverse operations gives 100\((1 - \gamma)\) percent GCI for \( \beta_0 \):
\[
\left[ b_0 - t_{n-2,\gamma/2} \times S(b_0), \ b_0 + t_{n-2,\gamma/2} \times S(b_0) \right],
\]
where,
\[ S(b_0) = \sqrt{(n/(n-2)) s_y^2 \left( 1/n + \bar{X}^2 / \sum (X_i - \bar{X})^2 \right)} \).

2.1.3 GCI for dispersion parameter

The GPQ for \( \sigma^2 \) is
\[ R_{\sigma^2} = \frac{\sigma^2}{S_Y^2} \times \frac{s_y^2}{\sigma^2} \frac{s_y^2}{S_Y^2 / \sigma^2} = \frac{ns_y^2}{nS_Y^2 / \sigma^2} = \frac{ns_y^2}{\chi^2_{n-2}}. \] (2.4)

To construct the 100\((1 - \gamma)\) percent GCI for \( \sigma^2 \) let
\[ Pr(R_{\sigma^2} < c) = 1 - \gamma/2. \]

Then,
\[ Pr \left( \frac{ns_y^2}{\chi^2_{n-2}} < c \right) = 1 - \gamma/2, \]
or,
\[ Pr \left( \chi^2_{n-2} > \frac{ns_y^2}{c} \right) = 1 - \gamma/2. \]

Suppose \( \chi^2_{n-2,\gamma/2} \) is the \( 100\gamma/2^{\text{th}} \) percentile of \( \chi^2_{n-2} \). It implies that
\[ \frac{ns_y^2}{c} = \chi^2_{n-2,\gamma/2}. \]
or,
\[ c = \frac{ns_y^2}{\chi_{n-2, \gamma/2}^2}. \]
Again \( Pr(R_{\sigma^2} < d) = \gamma/2 \) gives
\[ \frac{ns_y^2}{d^2} = \chi_{n-2, 1-\gamma/2}^2. \]
Therefore,
\[ d = \frac{ns_y^2}{\chi_{n-2, 1-\gamma/2}^2}. \]
Thus, the 100(1 - \gamma) percent GCI for \( \sigma^2 \) is
\[ [d, c] = \left[ \frac{ns_y^2}{\chi_{n-2, 1-\gamma/2}^2}, \frac{ns_y^2}{\chi_{n-2, \gamma/2}^2} \right]. \]

2.1.4 GCI for expected response for given X

Let \( \mu_X \) be the expected response for a given X, i.e.,
\[ \mu_X = E[Y \mid X] = \beta_0 + \beta_1 X. \]
Therefore, an estimate of \( \mu_X \) is
\[ \hat{\mu}_X = b_0 + b_1 X. \]
Since \( \hat{\mu}_X \) is a linear combination of two jointly normal random variables \( b_0 \) and \( b_1 \), \( \hat{\mu}_X \) is also normally distributed. Now,
\[ E[\hat{\mu}_X] = E[b_0 + b_1 X] = \beta_0 + \beta_1 X = \mu_X. \]
\[ V[\hat{\mu}_X] = V[b_0 + b_1 X] = V[\bar{Y} - b_1 \bar{X} + b_1 X] = V[\bar{Y} + b_1 (X - \bar{X})]. \]
One can verify that
\[ Cov[\bar{Y}, b_1] = E \left( \bar{\varepsilon} \times \frac{\sum (X_i - \bar{X})\varepsilon_i}{\sum (X_i - \bar{X})^2} \right) = \frac{\sum (X_i - \bar{X})\sigma^2}{n \sum (X_i - \bar{X})^2} = 0. \]
Then,

\[ V[\hat{\mu}_X] = \frac{\sigma^2}{n} + (X - \bar{X})^2 \sum \frac{\sigma^2}{(X_i - \bar{X})^2} = \sigma^2 \left( \frac{1}{n} + \frac{(X - \bar{X})^2}{\sum (X_i - \bar{X})^2} \right). \]

Therefore,

\[ \hat{\mu}_X \sim N \left( \mu_X, \sigma^2 \left( \frac{1}{n} + \frac{(X - \bar{X})^2}{\sum (X_i - \bar{X})^2} \right) \right). \]

The GPQ for \( \mu_X \) is

\[ R_{\mu_X} = \hat{\mu}_X - \frac{\hat{\mu}_X - \mu_X}{\sigma} \sqrt{\frac{1}{n} + \frac{(X - \bar{X})^2}{\sum (X_i - \bar{X})^2}} \times \frac{s_y}{s_Y}. \]

\[ = \hat{\mu}_X - \frac{Z}{\sqrt{s^2_x/s^2}} \times s_y \sqrt{\frac{1}{n} + \frac{(X - \bar{X})^2}{\sum (X_i - \bar{X})^2}}; \]

\[ = \hat{\mu}_X - T_{n-2} \sqrt{\frac{n}{(n - 2)}} \times s_y \left( \frac{1}{n} + \frac{(X - \bar{X})^2}{\sum (X_i - \bar{X})^2} \right) \]

which gives the 100(1 - \( \gamma \)) percent GCI for \( \mu_X \) as

\[ \left[ \hat{\mu}_X - t_{n-2,\gamma/2} \sqrt{\hat{V}(\hat{\mu}_X)}, \hat{\mu}_X + t_{n-2,\gamma/2} \sqrt{\hat{V}(\hat{\mu}_X)} \right], \]

where \( t_{n-2,\gamma/2} \) is the 100(1 - \( \gamma /2 \))th percentile of \( T_{n-2} \) and

\[ \hat{V}(\hat{\mu}_X) = \frac{n}{(n - 2)} s^2_x \left( \frac{1}{n} + \frac{(X - \bar{X})^2}{\sum (X_i - \bar{X})^2} \right). \]

### 2.2 Error distribution is normal with zero mean and varying dispersion

Consider the model

\[ Y_i = \beta_0 + \beta_1 X_i + \varepsilon_i, \text{ where } i = 1, 2, \ldots, n. \]

We assume independent \( \varepsilon_i \sim N(0, \sigma^2_i) \), where \( \sigma^2_i \) are not necessarily equal. Heterogeneous error variance is often observed in practice (Gujarati; 1995). In matrix notation, we can express the model as

\[ Y = X\beta + \varepsilon, \]
where

\[
Y = \begin{pmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_n \end{pmatrix}, X = \begin{pmatrix} 1 & X_1 \\ 1 & X_2 \\ \vdots \\ 1 & X_n \end{pmatrix}, \beta = \begin{pmatrix} \beta_1 \\ \beta_2 \end{pmatrix}, \varepsilon = \begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_n \end{pmatrix}.
\]

We assume that \(\varepsilon \sim N_n(0, V)\), where

\[
V = \begin{pmatrix} \sigma_1^2 & 0 & \ldots & 0 \\ 0 & \sigma_2^2 & \ldots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \ldots & \sigma_n^2 \end{pmatrix}.
\]

Often it is observed that variability increases as \(X\) increases. If we assume \(\sigma_i^2 = \sigma^2 X_i^2\), where \(\sigma^2\) is a constant, we can make the following transformation

\[
\frac{Y_i}{X_i} = \frac{\beta_0}{X_i} + \beta_1 + \frac{\varepsilon_i}{X_i}
\]
or

\[
\hat{Y}_i = \beta_0 \hat{X}_i + \beta_1 + \varepsilon_i.
\]

We may rewrite the above expression as

\[
\hat{Y}_i = \beta_1 + \beta_0 \hat{X}_i + \varepsilon_i. \quad (2.6)
\]

Now, \(\varepsilon_i \sim N(0, \sigma^2)\). Thus homoscedasticity is maintained in the model (2.6) and it becomes the usual estimation problem in simple linear regression with constant error variance and non-stochastic \(X\). For notational simplicity consider \(\hat{Y}_i\) as \(Y_i\), \(\hat{X}_i\) as \(X_i\) and \(\varepsilon_i\) as \(\varepsilon_i\). The maximum likelihood estimators for \(\beta_0\), \(\beta_1\) and \(\sigma^2\) are

\[
b_0 = \frac{\sum (X_i - \bar{X}) Y_i}{\sum (X_i - \bar{X})^2}, \quad b_1 = \bar{Y} - b_0 \bar{X} \quad \text{and} \quad S_Y^2 = \frac{\sum (Y_i - \hat{Y}_i)^2}{n},
\]

where \(\bar{X} = \sum X_i / n\), \(\bar{Y} = \sum Y_i / n\) and \(\hat{Y}_i = b_1 + b_0 X_i\). These estimators are distributed as

\[
\begin{pmatrix} b_1 \\ b_0 \end{pmatrix} \sim N_2 \left( \begin{pmatrix} \beta_1 \\ \beta_0 \end{pmatrix}, \sigma^2 \begin{pmatrix} \frac{1}{n} + \frac{\bar{X}^2}{\sum (X_i - \bar{X})^2} & -\frac{\bar{X}}{\sum (X_i - \bar{X})^2} \\ -\frac{\bar{X}}{\sum (X_i - \bar{X})^2} & \frac{1}{\sum (X_i - \bar{X})^2} \end{pmatrix} \right).
\]
and
\[ \frac{nS_Y^2}{\sigma^2} \sim \chi^2_{n-2}. \]
The GPQs for \( \beta_0, \beta_1 \) and \( \sigma^2 \) are obtained as before:

\[ R_{\beta_0} = b_0 - \frac{b_0 - \beta_0}{\sigma} \frac{\sqrt{\sum (X_i - \bar{X})^2}}{\sqrt{\sum (X_i - \bar{X})^2}} \times \frac{\sigma}{S_Y} \times \frac{s_y}{S_Y}, \]

\[ R_{\beta_1} = b_1 - \frac{b_1 - \beta_1}{\sigma} \frac{\sqrt{1/n + X^2 / \sum (X_i - \bar{X})^2}}{\sigma} \times \frac{\sigma}{S_Y} \times \frac{1}{S_Y} \times \frac{s_y}{S_Y}, \]

\[ R_{\sigma^2} = \frac{\sigma^2}{S_Y^2} \times \frac{s_y^2}{S_Y^2}, \]

where \( s_y^2 \) is observed value of \( S_Y^2 \).

### 2.3 Heteroscedasticity in two different regimes

Often data are collected in two different regimes, for example, the pre-depression period and the depression period. The dispersion in error terms remains the same within the regime but varies between regimes. Consider the model

\[ Y_i = \beta_0 + \beta_1 X_i + \varepsilon_i; \quad i = 1, 2, \ldots, n, \]

where \( \varepsilon_i \) is normally distributed with zero mean and

\[ \text{Var}(\varepsilon_i) = \begin{cases} \sigma_1^2 & \text{for } i = 1, 2, \ldots, n_1, \\ \sigma_2^2 & \text{for } i = n_1 + 1, n_1 + 2, \ldots, n. \end{cases} \]

In matrix notation

\[ Y = X\beta + \varepsilon, \]

here \( \varepsilon \sim N_n(0, V) \), where

\[ V = \begin{pmatrix} \sigma_1^2 I_{n_1} & 0 \\ 0 & \sigma_2^2 I_{n-n_1} \end{pmatrix}. \]
2.3.1 GCI\n    s for $\beta_0$ and $\beta_1$ when $\sigma_1^2$ and $\sigma_2^2$ are known

When $\sigma_1^2$ and $\sigma_2^2$ are known, the estimation problem is straightforward. The generalized least square estimates of regression parameters are obtained by

$$ b = (b_0(X, Y), b_1(X, Y))' = (X'V^{-1}X)^{-1}X'V^{-1}Y, $$

which follows a bivariate normal distribution as

$$ b \sim N_2(\beta, (X'V^{-1}X)^{-1}). $$

Suppose

$$(X'V^{-1}X)^{-1} = \begin{pmatrix} g_1(X, \sigma_1^2, \sigma_2^2) & g_{12}(X, \sigma_1^2, \sigma_2^2) \\ g_{12}(X, \sigma_1^2, \sigma_2^2) & g_2(X, \sigma_1^2, \sigma_2^2) \end{pmatrix},$$

where $g_1(X, \sigma_1^2, \sigma_2^2) = Var(b_0)$, $g_{12}(X, \sigma_1^2, \sigma_2^2) = Var(b_1)$ and $g_{12}(X, \sigma_1^2, \sigma_2^2) = Cov(b_0, b_1)$.

The GPQ for $\beta_0$ and $\beta_1$ are respectively:

$$ R_{\beta_0} = b_0(X, y) - \frac{b_0(X, Y) - \beta_0}{(g_1(X, \sigma_1^2, \sigma_2^2))^{1/2}} \times (g_1(X, \sigma_1^2, \sigma_2^2))^{1/2} $$

$$ = b_0(X, y) - Z \times (g_1(X, \sigma_1^2, \sigma_2^2))^{1/2} \quad (2.11) $$

and

$$ R_{\beta_1} = b_1(X, y) - \frac{b_1(X, Y) - \beta_1}{(g_2(X, \sigma_1^2, \sigma_2^2))^{1/2}} \times (g_2(X, \sigma_1^2, \sigma_2^2))^{1/2} $$

$$ = b_1(X, y) - Z \times (g_2(X, \sigma_1^2, \sigma_2^2))^{1/2}, \quad (2.12) $$

where $Z$ is $N(0, 1)$. Let $n_2 = n - n_1$ and introduce $j$ such that $i = n_1 + 1, n_1 + 2, \ldots, n$ is the same as $j = 1, 2, \ldots, n_2$. Then $g_1$ and $g_2$ can be expressed as

$$ g_1(X, \sigma_1^2, \sigma_2^2) = \frac{\sum X_i^2 / \sigma_1^2 + \sum X_i^2 / \sigma_2^2}{(n_1 / \sigma_1^2 + n_2 / \sigma_2^2)(\sum X_i^2 / \sigma_1^2 + \sum X_i^2 / \sigma_2^2) - (n_1 \bar{X}_1 / \sigma_1^2 + n_2 \bar{X}_2 / \sigma_2^2)^2}, $$

$$ g_2(X, \sigma_1^2, \sigma_2^2) = \frac{n_1 / \sigma_1^2 + n_2 / \sigma_2^2}{(n_1 / \sigma_1^2 + n_2 / \sigma_2^2)(\sum X_i^2 / \sigma_1^2 + \sum X_i^2 / \sigma_2^2) - (n_1 \bar{X}_1 / \sigma_1^2 + n_2 \bar{X}_2 / \sigma_2^2)^2}, $$
where $\bar{X}_1 = \sum X_i/n_1$ and $\bar{X}_2 = \sum X_j/n_2$. The generalized $(1 - \alpha)\%$ confidence intervals for $\beta_0$ and $\beta_1$ are, respectively

$$\left[ b_0(X, y) - Z_{a/2} \times (g_1(X, \sigma^2_1, \sigma^2_2))^{1/2}, b_0(X, y) + Z_{a/2} \times (g_1(X, \sigma^2_1, \sigma^2_2))^{1/2} \right]$$

and

$$\left[ b_1(X, y) - Z_{a/2} \times (g_2(X, \sigma^2_1, \sigma^2_2))^{1/2}, b_1(X, y) + Z_{a/2} \times (g_2(X, \sigma^2_1, \sigma^2_2))^{1/2} \right].$$

### 2.3.2 GCIs for $\beta_0$ and $\beta_1$ when $\sigma^2_1$ and $\sigma^2_2$ are unknown

When $\sigma^2_1$ and $\sigma^2_2$ are unknown, we propose weighted estimators for the regression parameters. First, independent estimates of regression parameters for the two regimes are obtained using the least square method and then weighted average of the estimates give the proposed estimates for the combined sample.

Suppose $b^{(i)}_0$, $b^{(i)}_1$ are least square estimates of $\beta_0$ and $\beta_1$ respectively and $\hat{\sigma}^2_i = S^2_i$ is the error mean square for regime $i$, where $i = 1, 2$. The proposed weighted estimator of $\beta_0$ is

$$b_0 = w_1 b^{(1)}_0 + (1 - w_1) b^{(2)}_0,$$

where $w_1$ is the weight for regime 1 and it is determined such that $Var(b_0)$ is minimum. Now,

$$Var(b_0) = w_1^2 Var\left(b^{(1)}_0\right) + (1 - w_1)^2 Var\left(b^{(2)}_0\right) = w_1^2 \sigma^2_1 f(X_1) + (1 - w_1)^2 \sigma^2_2 f(X_2)$$

where

$$f(X) = \frac{1}{n} + \frac{\bar{X}^2}{\sum (X_i - \bar{X})^2},$$

$X_1 = (X_1, X_2, \ldots, X_{n_1})$ and $X_2 = (X_{n_1+1}, X_{n_1+2}, \ldots, X_n)$. Differentiating $Var(b_0)$ with respect to $w_1$ and then equating it to 0 we get

$$2w_1 \sigma^2_1 f(X_1) - 2(1 - w_1) \sigma^2_2 f(X_2) = 0,$$
which gives
\[ w_1 = \frac{\sigma^2 f(X_2)}{\sigma_1^2 f(X_1) + \sigma_2^2 f(X_2)}. \]
The estimate is given by
\[ \hat{w}_1 = \frac{s_2^2 f(X_2)}{s_1^2 f(X_1) + s_2^2 f(X_2)}, \]
where \( s_1^2 \) and \( s_2^2 \) are the observed value of the error mean squares \( S_1^2 = \frac{\Sigma(Y_i - \hat{Y}_i)^2}{n_1 - 2} \) and \( S_2^2 = \frac{\Sigma(Y_i - \hat{Y}_i)^2}{n_2 - 2} \), respectively.

Therefore,
\[ b_0 = \hat{w}_1 b_0^{(1)} + (1 - \hat{w}_1) b_0^{(2)}. \]

Using (2.3) the GPQ for \( \beta_0 \) for regime \( i \) is
\[ R_{\beta_0} = b_0^{(i)} - \frac{b_0^{(i)} - \beta_0}{\sigma_i \sqrt{f(X_i)}} \times \sigma_i \sqrt{f(X_i)} \times \frac{s_i}{S_i} = b_0^{(i)} - T_{n_i - 2} \times s_i \sqrt{f(X_i)}. \quad (2.13) \]

Therefore, the GPQ for \( \beta_0 \) for combined sample is
\[ R_{\beta_0} = \hat{w}_1 R_{\beta_0}^{(1)} + (1 - \hat{w}_1) R_{\beta_0}^{(2)}. \quad (2.14) \]

For observed \( y \) of \( Y \), \( R_{\beta_0} \) is equal to \( \beta_0 \) and its distribution is independent of any unknown parameters. The 100\( \alpha/2 \)th and 100\( (1 - \alpha/2) \)th percentiles of \( R_{\beta_0} \) form a 100(1 – \( \alpha \)) percent GCI for it. The percentiles can be obtained through simulation.

Similarly, the GPQ for \( \beta_1 \) is
\[ R_{\beta_1} = \hat{\delta}_1 R_{\beta_1}^{(1)} + (1 - \hat{\delta}_1) R_{\beta_1}^{(2)}, \quad (2.15) \]

where \( R_{\beta_1}^{(i)} \) is the GPQ for \( \beta_1 \) for regime \( i, i = 1, 2 \). Now, \( R_{\beta_1}^{(i)} \) is defined as
\[ R_{\beta_1}^{(i)} = b_1^{(i)} - \frac{b_1^{(i)} - \beta_1}{\sigma_i \sqrt{f^*(X_i)}} \times \sigma_i \sqrt{f^*(X_i)} \times \frac{s_i}{S_i} = b_1^{(i)} - T_{n_i - 2} \times s_i \sqrt{f^*(X_i)}, \quad (2.16) \]
where
\[ f^*(X) = \frac{1}{\sum (X_i - \bar{X})^2} \]
and \( \hat{\delta}_1 \) is the estimated weight which is defined as
\[ \hat{\delta}_1 = \frac{s_2^2 f^*(X_2)}{s_1^2 f^*(X_1) + s_2^2 f^*(X_2)}. \]
The GCI for \( \beta_1 \) can then be obtained by getting the percentiles of \( R_{\beta_1} \) through simulation.

The GPQ for \( \sigma_i^2 \) is
\[ R_{\sigma_i^2} = \frac{\sigma_i^2}{\bar{S}_i^2} \times s_i^2 = \frac{(n_i - 2)s_i^2}{\chi^2_{n_i - 2}}. \]  
(2.17)

2.4 Testing equality of corresponding regression coefficients under heteroscedasticity

Consider the regression model
\[ \begin{cases} 
Y_i = \beta_{10} + \beta_{11}X_i + \varepsilon_i, & i = 1, 2, \ldots, n_1, \\
Y_j = \beta_{20} + \beta_{21}X_j + \varepsilon_j, & j = 1, 2, \ldots, n_2, 
\end{cases} \]  
(2.18)

where \( n_2 = n - n_1 \) with \( \varepsilon_i \ iid \ N(0, \sigma_1^2) \) and \( \varepsilon_j \ iid \ N(0, \sigma_2^2) \). Also, \( \varepsilon_i \) and \( \varepsilon_j \) are independent.

We would like to test the hypotheses
\[ H_{01} : \beta_{10} = \beta_{20} \text{ against } H_{11} : \beta_{10} \neq \beta_{20} \text{ and } \]
\[ H_{02} : \beta_{11} = \beta_{21} \text{ against } H_{12} : \beta_{11} \neq \beta_{21}. \]
To test the hypotheses, we propose GPQs for the difference of the corresponding regression coefficients of two regimes. Our proposed GPQs can be used efficiently in testing the hypotheses irrespective of the sample sizes of the regimes. We will
illustrate the construction of the GPQ for $\beta_{10} - \beta_{20}$. The GPQ for $\beta_{11} - \beta_{21}$ can be obtained in a similar fashion.

We know that

$$b_{10}(X_1, Y_1) \sim N(\beta_{10}, \sigma_1^2 f(X_1)), \quad b_{20}(X_2, Y_2) \sim N(\beta_{20}, \sigma_2^2 f(X_2)),$$

where,

$$f(X) = \frac{1}{n} + \frac{\bar{X}^2}{\sum (X_i - \bar{X})^2}.$$

$Y_1 = (Y_1, Y_2, \ldots, Y_{n_1}), \ Y_2 = (Y_{n_1+1}, Y_{n_1+2}, \ldots, Y_n), \ X_1 = (X_1, X_2, \ldots, X_{n_1})$ and $X_2 = (X_{n_1+1}, X_{n_1+2}, \ldots, X_n)$.

Again, (see Appendix A.1)

$$\frac{(n_1 - 2)S_1^2}{\sigma_1^2} \sim \chi^2_{n_1-2} \quad \text{and} \quad \frac{(n_2 - 2)S_2^2}{\sigma_2^2} \sim \chi^2_{n_2-2},$$

where $S_1^2 = \frac{\sum (Y_i - \bar{Y})^2}{n_1-2}$ and $S_2^2 = \frac{\sum (Y_i - \bar{Y})^2}{n_2-2}$ are the error mean squares for regimes 1 and 2, respectively. Further, these four random variables $b_{10}, \ b_{20}, \ S_1^2$ and $S_2^2$ are independent of each other, since $b_{i0}$ and $S_i^2, \ i = 1, 2$, are independent of each other (Appendix A.2) and the samples from the two regimes are independent.

Therefore,

$$b_{10}(X_1, Y_1) - b_{20}(X_2, Y_2) \sim N(\beta_{10} - \beta_{20}, \sigma_1^2 f(X_1) + \sigma_2^2 f(X_2)).$$

The proposed GPQ for $\beta_{10} - \beta_{20}$ is

$$R_{\beta_{10} - \beta_{20}} = b_{10}(X_1, y_1) - b_{20}(X_2, y_2) - \left(\frac{b_{10}(X_1, Y_1) - b_{20}(X_2, Y_2) - (\beta_{10} - \beta_{20})}{(\sigma_1^2 f(X_1) + \sigma_2^2 f(X_2))^{1/2}}\right)$$

$$\times \left(\sigma_1^2 f(X_1) \frac{S_1^2}{S_1^2} + \sigma_2^2 f(X_2) \frac{S_2^2}{S_2^2}\right)^{1/2}. \quad (2.19)$$

Then,

$$R_{\beta_{10} - \beta_{20}} = b_{10}(X_1, y_1) - b_{20}(X_2, y_2) - Z \left(\frac{s_1^2 f(X_1)}{S_1^2/\sigma_1^2} + \frac{s_2^2 f(X_2)}{S_2^2/\sigma_2^2}\right)^{1/2}.$$
Chapter 2. Generalized Confidence Intervals for Simple Linear Regression Parameters

with $Z \sim N(0, 1)$.

Further, we have

$$R_{\beta_{10}-\beta_{20}} = b_{10}(X_1, y_1) - b_{20}(X_2, y_2) - Z \left( \frac{(n_1 - 2)s_1^2 f(X_1)}{\chi_{n1-2}^2} + \frac{(n_2 - 2)s_2^2 f(X_2)}{\chi_{n2-2}^2} \right)^{1/2}$$

$$= b_{10}(X_1, y_1) - b_{20}(X_2, y_2) - \frac{Z}{\left( \frac{\chi_{n1-2}^2 + \chi_{n2-2}^2}{n_1 + n_2 - 4} \right)^{1/2}} \cdot \left( \frac{(n_1 - 2)s_1^2 f(X_1)}{\chi_{n1-2}^2} + \frac{(n_2 - 2)s_2^2 f(X_2)}{\chi_{n2-2}^2} \right)^{1/2} \times \left( \frac{\chi_{n1-2}^2}{n_1 + n_2 - 4} \right)^{1/2},$$

and finally,

$$R_{\beta_{10}-\beta_{20}} = b_{10}(X_1, y_1) - b_{20}(X_2, y_2) - T_{n1+n2-4}$$

$$\times \left( \frac{1}{n_1 + n_2 - 4} \left( \frac{(n_1 - 2)s_1^2 f(X_1)}{B} + \frac{(n_2 - 2)s_2^2 f(X_2)}{1 - B} \right) \right)^{1/2}, (2.20)$$

where

$$B = \frac{\chi_{n1-2}^2}{\chi_{n1-2}^2 + \chi_{n2-2}^2} \sim Beta\left(\frac{n_1 - 2}{2}, \frac{n_2 - 2}{2}\right).$$

We have seen from (2.19) for observed sample $R_{\beta_{10}-\beta_{20}}$ is equal to $\beta_{10} - \beta_{20}$. We also observe that its distribution is independent of any unknown parameters.

Similarly, the proposed GPQ for $\beta_{11} - \beta_{21}$ is

$$R_{\beta_{11}-\beta_{21}} = b_{11}(X_1, y_1) - b_{21}(X_2, y_2) - \left( \frac{b_{11}(X_1, Y_1) - b_{21}(X_2, Y_2) - (\beta_{11} - \beta_{21})}{(\sigma_1^2 f^*(X_1) + \sigma_2^2 f^*(X_2))^{1/2}} \right)$$

$$\times \left( \frac{\sigma_1^2 f^*(X_1) s_1^2}{S_1} + \frac{\sigma_2^2 f^*(X_2) s_2^2}{S_2} \right)^{1/2}, (2.21)$$

where

$$f^*(X) = \frac{1}{\sum (X_i - \bar{X})^2}.$$}

Then,

$$R_{\beta_{11}-\beta_{21}} = b_{11}(X_1, y_1) - b_{21}(X_2, y_2) - T_{n1+n2-4}$$

$$\times \left( \frac{1}{n_1 + n_2 - 4} \left( \frac{(n_1 - 2)s_1^2 f^*(X_1)}{B} + \frac{(n_2 - 2)s_2^2 f^*(X_2)}{1 - B} \right) \right)^{1/2}, (2.22)$$
Chapter 2. Generalized Confidence Intervals for Simple Linear Regression Parameters

The percentiles of \(R_{\beta_{10} - \beta_{20}}\) and \(R_{\beta_{11} - \beta_{21}}\) would give the GCIs for \(\beta_{10} - \beta_{20}\) and \(\beta_{11} - \beta_{21}\) respectively. The percentiles can be obtained using simulation.

The generalized p-values for testing the equality of intercepts and slopes are respectively

\[
P_{\beta_{10} - \beta_{20}} = 2 \min \{P(R_{\beta_{10} - \beta_{20}} \geq 0), P(R_{\beta_{10} - \beta_{20}} \leq 0)\} \quad (2.23)
\]

and

\[
P_{\beta_{11} - \beta_{21}} = 2 \min \{P(R_{\beta_{11} - \beta_{21}} \geq 0), P(R_{\beta_{11} - \beta_{21}} \leq 0)\}. \quad (2.24)
\]
Chapter 3

Generalized Inference for Multiple Linear Regression Parameters

In this chapter we make generalized inference on parameters of a multiple linear regression model for a fixed set of values of the explanatory variables. Different assumptions are made about the error distribution. Consider the multiple linear regression model

\[ Y_j = \beta_1 X_{1j} + \beta_2 X_{2j} + \ldots + \beta_p X_{pj} + \varepsilon_j, \quad j = 1, 2, \ldots, n. \]  

(3.1)

Here \( Y_j \) is the response variable for the \( j^{th} \) set of values of \((X_1, X_2, \ldots, X_p)\) and \( \varepsilon_j \) is the corresponding random error term. Also, \( \beta_i, \ i = 1, 2, \ldots, p \) represent a total of \( p \) unknown parameters to be estimated. Intercept can be included in the model by defining \( X_{1j} = 1 \) for all \( j \). In section 3.1, we assume iid normal errors with zero mean and constant variance. Then, we construct the generalized confidence region for the regression parameters’ vector and generalized confidence interval for the regression coefficients. We also construct generalized confidence interval for the dispersion parameter. In section 3.2, heteroscedasticity in error terms is considered. We assume that variability in error terms is due to the measurement errors in one particular explanatory variable. Multivariate data from two different regimes with heteroscedasticity are considered in section 3.3. As in the simple linear regression case, we assume that the regression coefficients remain the same for the two regimes.
and that the error variance is stationary within the regime but different between regimes. In such case, we propose generalized confidence regions and confidence intervals for the regression parameters’ vector and regression coefficients, respectively. In section 3.4, we test the equality of the sets regression coefficients of two regimes under heteroscedasticity. Chow (1960) proposed a test to do this task in the homoscedastic case. Later, Toyoda (1974) extended the Chow test for heteroscedastic regimes. He showed that the test is appropriate when the regimes’ error variances are equal. Under heteroscedasticity the test works well if at least one regime has large sample size. If both regimes have small sample sizes, its level of significance is affected greatly even for moderate heteroscedasticity. For this multivariate Behrens-Fisher problem we propose a generalized test variable that can be used efficiently in testing the equality of the sets regression coefficients of the two regimes irrespective of their sample sizes. The generalized p-value for this test is given. We construct the generalized confidence region for the difference of the two sets of regression coefficients and then, the generalized confidence intervals for elements of that vector. Note that in the definition of GTV, given in section 1.1, the third property refers to the case where \( \theta \in \mathbb{R} \). For the case where \( \theta \in \mathbb{R}^n \), the concept of monotonocity needs some clarifications since the concept of order is not clearly defined in \( \mathbb{R}^n \). Let, the norm of a vector \( x \in \mathbb{R}^n \) is \( \| x \|_A^2 = x'Ax \), where \( A \) is a positive definite matrix. We consider that the vector \( x \) is less than the vector \( y \in \mathbb{R}^n \) \( (x < y) \) if

\[
\| x \|_A < \| y \|_A.
\]

for any positive definite matrix \( A \). Thus, a real valued function over \( \mathbb{R}^n \), say, \( f(x) \), \( x \in \mathbb{R}^n \) is considered to be non-decreasing if for all \( x_1 < x_2 \in \mathbb{R}^n \) we have

\[
f(x_1) \leq f(x_2).
\]
3.1 Error terms are normal random variables with zero mean and constant variance

Suppose error terms \( \varepsilon_j, j = 1, 2, \ldots, n \) are iid normal with zero mean and constant variance \( \sigma^2 \). Defining

\[
Y = \begin{pmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_n \end{pmatrix}, \quad \beta = \begin{pmatrix} \beta_1 \\ \beta_2 \\ \vdots \\ \beta_p \end{pmatrix}, \quad X = \begin{pmatrix} X_{11} & X_{21} & \cdots & X_{p1} \\ X_{12} & X_{22} & \cdots & X_{p2} \\ \vdots & \vdots & \ddots & \vdots \\ X_{1n} & X_{2n} & \cdots & X_{pn} \end{pmatrix} \quad \text{and} \quad \varepsilon = \begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_n \end{pmatrix},
\]

the model in (3.1) can be written in matrix notation as

\[
Y = X\beta + \varepsilon, \tag{3.2}
\]

where \( X \) has full column rank.

3.1.1 Generalized confidence region (GCR) for \( \beta \)

Given model (3.2), the least squares estimator for \( \beta \) is

\[
\hat{\beta} = b = (X'X)^{-1}X'Y, \quad \text{where} \quad b = (b_1, b_2, \ldots, b_p)',
\]

and given the normality assumption on \( \varepsilon \),

\[
b \sim N_p\left(\beta, \sigma^2(X'X)^{-1}\right)
\]

and by the result in Appendix A.1,

\[
\frac{(n-p)S^2}{\sigma^2} \sim \chi^2_{n-p},
\]

where

\[
S^2 = (Y - \hat{Y})'(Y - \hat{Y})/(n-p) = \sum_{j=1}^{n}(Y_j - \hat{Y}_j)^2/(n-p) = \text{Error MS}.
\]

Let us define

\[
T = (s^2(X'X)^{-1})^{-1/2}b,
\]
\[ \Lambda = \left( s^2 (X'X)^{-1} \right)^{-1/2} \sigma^2 (X'X)^{-1} \left( s^2 (X'X)^{-1} \right)^{-1/2}, \]

\[ \theta = \left( s^2 (X'X)^{-1} \right)^{-1/2} \beta, \]

where \( s^2 \) is the observed value of \( S^2 \).

Therefore,

\[ T \sim N_p(\theta, \Lambda). \]

It implies that

\[ U = (T - \theta)' \Lambda^{-1} (T - \theta) \sim \chi^2_p. \]

One can verify that

\[ U = \frac{1}{\sigma^2} (b - \beta)' (X'X) (b - \beta). \]

Further, let

\[ V = \frac{S^2}{\sigma^2 s^2}. \]

One can verify that

\[ V \sim \frac{1}{(n - p) s^2} \chi^2_{n-p}. \]

Again, \( U \) and \( V \) are independent of each other (see Appendix A2). Therefore,

\[ F = \frac{U/p}{V} = \frac{1}{s^2} \frac{(b - \beta)' (X'X) (b - \beta)/p}{\frac{S^2}{\sigma^2 s^2}} = s^2 F_{p, n-p}, \]  

(3.3)

where \( F_{p, n-p} \) has Fishers’s distribution with \( (p, n-p) \) degrees of freedom. Note that, for given \( Y \) and \( \beta \) the distribution of \( F \) is free of the nuisance parameter \( \sigma^2 \). Also, under \( H_0 : \beta = \beta_0 \), the observed value of \( F \) is

\[ f_0 = \frac{1}{p} (b - \beta_0)' (X'X) (b - \beta_0) \]  

(3.4)
that does not depend on $\sigma^2$. Further, the observed value of $F$ is

$$f = \frac{1}{p}(b - \beta)'(X'X)(b - \beta),$$

a positive definite quadratic form in $(b - \beta)$. For given $y$, $f$ is a non-decreasing function of $\beta$. It implies that $P(F \geq f)$ is stochastically non-increasing in $\beta$. Therefore, $F$ is the generalized test variable for testing $H_0 : \beta = \beta_0$. The generalized p-value is

$$P(F \geq f_0).$$

Now, this generalized test variable $F$ can be used to obtain a GCR for $\beta$. In fact, in multiparameter problems, generalized pivotal quantities are difficult or impossible to obtain. Instead, the distribution of a generalized test variable can be used to derive a generalized confidence region (Gamage et al; 2004). Let $F_{p, n-p, 1-\alpha}$ is the $100(1-\alpha)^{th}$ percentile of Fisher’s distribution with $(p, n-p)$ degrees of freedom. Then

$$P(F \leq s^2F_{p, n-p, 1-\alpha}) = 1 - \alpha.$$ 

The 100$(1 - \alpha)$ percent generalized confidence region (GCR) for the elements of $\beta$ is represented by the set of values of the vector $b$ which satisfy the following inequality

$$(b - \beta)'(X'X)(b - \beta) \leq ps^2F_{p, n-p, 1-\alpha}.$$  \hspace{1cm} (3.5)

### 3.1.2 Generalized confidence interval (GCI) for $\beta_i$

Suppose,

$$\sigma^2(X'X)^{-1} = \sigma^2 \begin{pmatrix} d_{11} & d_{12} & \ldots & d_{1p} \\ d_{21} & d_{22} & \ldots & d_{2p} \\ \vdots & \vdots & \ddots & \vdots \\ d_{p1} & d_{p2} & \ldots & d_{pp} \end{pmatrix}.$$ 

Denote the generalized pivotal quantity for $\beta_i$ by $R_{\beta_i}$. Then

$$R_{\beta_i} = b_i - \frac{b_i - \beta_i}{\sigma \sqrt{d_{ii}}} \times \sigma \sqrt{d_{ii}} \times \frac{s_y}{S_Y},$$  \hspace{1cm} (3.6)
where \( s_y^2 \) is the observed value of

\[
S_Y^2 = \sum_{j=1}^{n} (Y_j - \hat{Y}_j)^2 / n.
\]

Note that \( \frac{nS_Y^2}{\sigma^2} \sim \chi^2_{n-p} \). One can verify that

\[
R_{\beta_i} = b_i - T_{n-p} \sqrt{\frac{n}{n-p} s_y^2 d_{ii}} ,
\]

where \( T_{n-p} \) has a t-distribution with \( n-p \) degrees of freedom. We would like to construct generalized confidence intervals for \( \beta'_i \)'s. There are \( p \) of them. If we construct 100(1 - \( \alpha \)) percent generalized confidence intervals for each of them, the probability that the \( p \) intervals will simultaneously be correct is at least \( 1 - p\alpha \). If \( p \) is large, the set of generalized confidence intervals becomes relatively uninformative.

There are several approaches to maintain the overall confidence level to be at least \( 1 - \alpha \). Among them Bonferroni approach (Alt; 1982), Scheffe method (Scheffe; 1959) and Working-Hotelling approach (Working and Hotelling; 1929) are widely used. For simplicity we consider the Bonferroni technique of splitting \( \alpha \). We construct generalized confidence intervals for \( \beta'_i \)'s each with confidence coefficient \( 1 - \alpha/p \). In this way we maintain the overall confidence level to be at least \( 1 - \alpha \). Therefore, the 100(1 - \( \alpha \)) percent joint generalized confidence intervals for \( \beta'_i \)'s are

\[
\left( b_i - t_{n-p, \alpha/2p} \sqrt{\frac{n}{n-p} s_y^2 d_{ii}}, b_i + t_{n-p, \alpha/2p} \sqrt{\frac{n}{n-p} s_y^2 d_{ii}} \right),
\]

where \( t_{n-p, \alpha/2p} \) is the 100(1 - \( \alpha/2p \))th percentile of \( T_{n-p} \). The limitation of the Bonferroni approach is that when \( p \) is large, it will give conservative results. In such case, the other methods of maintaining overall confidence level can be applied in generalized inference.
3.1.3 GCI for dispersion parameter

The GPQ for $\sigma^2$ is

$$R_{\sigma^2} = \frac{\sigma^2}{S_Y^2} \times s_y^2.$$

One can verify that

$$R_{\sigma^2} = \frac{n s_y^2}{\chi_{n-p}^2}$$

Therefore, a $100(1 - \gamma)$ percent GCI for $\sigma^2$ is

$$\left( \frac{n s_y^2}{\chi_{n-p,1-\gamma/2}^2}, \frac{n s_y^2}{\chi_{n-p,\gamma/2}^2} \right),$$

where $\chi_{n-p,1-\gamma/2}^2$ is the $100(1 - \gamma/2)^{th}$ percentile of $\chi_{n-p}^2$.

3.2 Error distribution is normal with zero mean and varying dispersion

Consider the model

$$Y_j = \beta_1 X_{1j} + \beta_2 X_{2j} + \ldots + \beta_p X_{pj} + \varepsilon_j, \ j = 1, 2, \ldots, n.$$

We assume independent $\varepsilon_j \sim N(0, \sigma_j^2)$, where $\sigma_j^2$ are not necessarily equal. In matrix notation

$$Y = X\beta + \varepsilon.$$

Here, we assume that $\varepsilon \sim N_n(0, V)$, where

$$V = \begin{pmatrix}
\sigma_1^2 & 0 & \ldots & 0 \\
0 & \sigma_2^2 & \ldots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
0 & 0 & \ldots & \sigma_n^2
\end{pmatrix}.$$

Often this heteroscedasticity in error variance is due to systematic errors in measurements of one or more explanatory variables. For instance, suppose $\sigma_j^2 = \sigma^2 X_{ij}^2$, where
\( \sigma^2 \) is a constant. We can make the following transformation to stabilize the error variance:

\[
\frac{Y_j}{X_{ij}} = \beta_1 \frac{X_{1j}}{X_{ij}} + \beta_2 \frac{X_{2j}}{X_{ij}} + \ldots + \beta_i \frac{X_{ij}}{X_{ij}} + \ldots + \beta_p \frac{X_{pj}}{X_{ij}} + \varepsilon_j.
\]

Or,

\[
Y'_j = \beta_1 X'_{1j} + \beta_2 X'_{2j} + \ldots + \beta_i X'_{ij} + \ldots + \beta_p X'_{pj} + \varepsilon'_j, \tag{3.9}
\]

with \( X'_{ij} = 1 \) for \( \forall j \) and \( \varepsilon'_j \sim N(0, \sigma^2) \). Therefore, the model (3.9) becomes a multiple linear regression model with normal and homoscedastic error term and non-stochastic \( X \). GCR for \( \beta \) and GCIs for \( \beta_i \) and \( \sigma^2 \) can be obtained as explained in section 3.1.

### 3.3 Heteroscedasticity in two different regimes

Consider the model

\[
Y_j = \beta_1 X_{1j} + \beta_2 X_{2j} + \ldots + \beta_p X_{pj} + \varepsilon_j, \quad j = 1, 2, \ldots, n,
\]

where \( \varepsilon_j \) is normally distributed with zero mean and

\[
\text{Var}(\varepsilon_j) = \begin{cases} 
\sigma_1^2 & \text{for } j = 1, 2, \ldots, n_1 \\
\sigma_2^2 & \text{for } j = n_1 + 1, n_1 + 2, \ldots, n
\end{cases}
\]

i.e. \( \sigma_1^2 \) and \( \sigma_2^2 \) are error variances in the two different regimes. In matrix notation

\[
Y = X\beta + \varepsilon,
\]

where \( \varepsilon \sim N_n(0, V) \) and

\[
V = \begin{pmatrix} \sigma_1^2 I_{n_1} & 0 \\ 0 & \sigma_2^2 I_{n-n_1} \end{pmatrix}.
\]

#### 3.3.1 GCR and GCI for regression coefficients when \( \sigma_1^2 \) and \( \sigma_2^2 \) are known

For the known variance case, the least squares estimators of regression parameters are

\[
\hat{\beta} = b = (b_1, b_2, \ldots, b_p)' = (X'V^{-1}X)^{-1}X'V^{-1}Y,
\]
and \( b \) follows a \( p \)-variate normal distribution:

\[
b \sim N_p \left( \beta, (X'V^{-1}X)^{-1} \right).
\]

Therefore,

\[
(b - \beta)'(X'V^{-1}X)(b - \beta) \sim \chi^2_p.
\]

A \( 100(1 - \gamma) \) percent GCR for \( \beta \) is the set of values of \( b \) which satisfy the following inequality

\[
(b - \beta)'(X'V^{-1}X)(b - \beta) \leq \chi^2_{p, 1-\gamma/2},
\]

where \( \chi^2_{p, 1-\gamma/2} \) is the \( 100(1 - \gamma/2) \)th percentile of \( \chi^2_p \) distribution. Further, suppose

\[
(X'V^{-1}X)^{-1} = \begin{pmatrix}
g_{11} & g_{12} & \cdots & g_{1p} \\
g_{21} & g_{22} & \cdots & g_{2p} \\
\vdots & \vdots & \ddots & \vdots \\
g_{p1} & g_{p2} & \cdots & g_{pp}
\end{pmatrix},
\]

where \( g_{kk} \) is the variance of \( b_k \) and \( g_{kk'} \) is the covariance of \( b_k \) and \( b_{k'}, \ k \neq k' = 1, 2, \ldots, p \). Then GPQ for \( \beta_k \) is

\[
R_{\beta_k} = b_k - \frac{b_k - \beta_k}{\sqrt{g_{kk}}} \times \sqrt{g_{kk}} = b_k - Z\sqrt{g_{kk}},
\]

where \( Z \sim N(0, 1) \). Therefore, a \( 100(1 - \gamma) \) percent joint generalized confidence intervals for \( \beta_k \) s are

\[
(b_k - Z_{\gamma/2p}\sqrt{g_{kk}}, b_k + Z_{\gamma/2p}\sqrt{g_{kk}}),
\]

where \( Z_{\gamma/2p} \) is the \( 100(1 - \gamma/2p) \)th percentile of \( Z \).

### 3.3.2 GCR and GCI for regression coefficients when \( \sigma_1^2 \) and \( \sigma_2^2 \) are unknown

Let us partition the model \( Y = X \beta + \varepsilon \) for the two regimes as

\[
\begin{pmatrix}
Y_1 \\
Y_2
\end{pmatrix} = \begin{pmatrix}
X_1 \\
X_2
\end{pmatrix} \beta + \begin{pmatrix}
\varepsilon_1 \\
\varepsilon_2
\end{pmatrix},
\]
where $Y_1$ is of order $(n_1 \times 1)$ representing responses for the first regime,

$Y_2$ is of order $(n - n_1 \times 1)$ representing responses for the second regime,

$X_1$ is the design matrix of order $(n_1 \times p)$ for the first regime,

$X_2$ is the design matrix of order $(n - n_1 \times p)$ for the second regime,

$\beta$ is the $(p \times 1)$ vector of regression coefficients,

$\varepsilon_1$ is the $(n_1 \times 1)$ error vector for regime 1 and

$\varepsilon_2$ is the $(n - n_1 \times 1)$ error vector for regime 2.

Then, we have in matrix notation the model for the $i^{th}$ regime

$$Y_i = X_i \beta + \varepsilon_i, \quad i = 1, 2,$$

where $\varepsilon_i \sim N_{n_i}(0, \sigma_i^2 I_{n_i})$. The generalized test variable for the $i^{th}$ regime is

$$F_i = \frac{\frac{1}{\sigma_i^2}(b_i - \beta)'(X_i'X_i)(b_i - \beta)/p}{\frac{s_i^2}{\sigma_i^2 s_i^4}} = \frac{s_i^2}{\sigma_i^2 s_i^4} F_{p, n_i - p}, \quad (3.13)$$

where $s_i^2$ is the observed value of $S_i^2 = \text{Error MS for regime } i$, $F_{p, n_i - p}$ has a $F$ distribution with $(p, n_i - p)$ degrees of freedom and

$$\hat{\beta}_i = b_i = (b_{i1}, b_{i2}, \ldots, b_{ip})' = (X_i'X_i)^{-1}X_i'Y_i, \quad i = 1, 2.$$

Let us define

$$F = \eta_1 F_1 + (1 - \eta_1) F_2 = \eta_1 s_1^2 F_{p, n_1 - p} + (1 - \eta_1) s_2^2 F_{p, n_2 - p}.$$ 

$\eta_1$ is determined in such a way that $\text{Var}(F)$ is minimum. One can verify that

$$\hat{\eta}_1 = \frac{s_2^2 V_2}{s_1^2 V_1 + s_2^2 V_2},$$

where

$$V_i = \text{Var}(F_{p, n_i - p}) = \frac{2(n_i - p)^2(n_i - 2)}{p(n_i - p - 2)^2(n_i - p - 4)} \quad \text{for } n_i - p > 4, \quad i = 1, 2.$$ 

Let $F_\gamma$ satisfy $Pr(F \leq F_\gamma) = 1 - \gamma$. We can obtain $F_\gamma$ through simulation. Then 100(1 $- \gamma$) percent GCR for $\beta$ is obtained by the set of values of the vectors $b_1$ and $b_2$ which satisfy the following inequality

$$\hat{\eta}_1 (b_1 - \beta)'(X_1'X_1)(b_1 - \beta) + (1 - \hat{\eta}_1) (b_2 - \beta)'(X_2'X_2)(b_2 - \beta) \leq pF_\gamma. \quad (3.14)$$
Further, suppose

$$Cov(b_i) = \sigma_i^2 (X_i'X_i)^{-1} = \sigma_i^2 \begin{pmatrix}
  d_{i11} & d_{i12} & \ldots & d_{i1p} \\
  d_{i21} & d_{i22} & \ldots & d_{i2p} \\
  \vdots & \vdots & \ddots & \vdots \\
  d_{ip1} & d_{ip2} & \ldots & d_{ipp}
\end{pmatrix},$$

where $\sigma_i^2 d_{ikk}$ is the variance of the least square estimator of $\beta_k$ and $\sigma_i^2 d_{ikk}$ is the covariance between the least square estimators of $\beta_k$ and $\beta_{k'}$ for $k \neq k' = 1, 2, \ldots, p$ for the $i$th regime. The generalized pivotal quantity for $\beta_k$ is

$$R_{\beta_k} = \hat{w}_k R_{\beta_k}^{(1)} + (1 - \hat{w}_k) R_{\beta_k}^{(2)},$$

(3.15)

where $R_{\beta_k}^{(i)}$ is the GPQ for $\beta_k$ from the $i$th regime and

$$R_{\beta_k}^{(i)} = b_{ik} - T_{ni-p} \times s_i \sqrt{d_{ikk}}.$$  

(3.16)

Here $s_i^2$ is the observed value of $S_i^2$, the error mean square for regime $i$ and

$$\hat{w}_k = \frac{s_i^2 d_{2kk}}{s_i^2 d_{1kk} + s_i^2 d_{2kk}}$$

is the estimated weight factor.

### 3.4 Testing equality of corresponding regression coefficients under heteroscedasticity

In section 3.3 we consider the case where the regression coefficients remained the same for the two regimes, only the error variances were different between regimes. In this section, we like to test the equality of the regression coefficients of the two regimes under heteroscedasticity. Consider the regression models

$$\begin{cases}
  Y_{1j} = \beta_{11} X_{11j} + \beta_{12} X_{12j} + \ldots + \beta_{1p} X_{1pj} + \varepsilon_{1j}, & j = 1, 2, \ldots, n_1, \\
  Y_{2j} = \beta_{21} X_{21j} + \beta_{22} X_{22j} + \ldots + \beta_{2p} X_{2pj} + \varepsilon_{2j}, & j = 1, 2, \ldots, n_2,
\end{cases}$$

(3.17)
where \( \varepsilon_{1j} \sim iid N(0, \sigma_1^2) \) and \( \varepsilon_{2j} \sim iid N(0, \sigma_2^2) \). In matrix notation

\[
\begin{align*}
Y_1 &= X_1 \beta_1 + \varepsilon_1, \\
Y_2 &= X_2 \beta_2 + \varepsilon_2,
\end{align*}
\]

where \( \beta_i = (\beta_{i1}, \beta_{i2}, \ldots, \beta_{ip})' \),

\( \varepsilon_i = (\varepsilon_{i1}, \varepsilon_{i2}, \ldots, \varepsilon_{in_i})' \sim N_{n_i}(0, \sigma_i^2 I_{n_i}) \),

\( \varepsilon_1 \) and \( \varepsilon_2 \) are independent,

\( Y_i = (Y_{i1}, Y_{i2}, \ldots, Y_{in_i})' \) and

\( X_i \) is the design matrix of order \((n_i \times p)\) for the \( i^{th} \) regime.

The least squares estimators of the regression parameters for the \( i^{th} \) regime is

\[
\hat{\beta}_i = b_i = (b_{i1}, b_{i2}, \ldots, b_{ip})' = (X_i'X_i)^{-1}X_i'Y_i.
\]

An unbiased estimator for the error variance \( \sigma_i^2 \) is \( S_i^2 \), error mean square for regime \( i \).

Further,

\[
\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} \sim N_{2p} \left( \begin{pmatrix} \beta_1 \\ \beta_2 \end{pmatrix}, \begin{pmatrix} \sigma_1^2(X_1'X_1)^{-1} & 0 \\ 0 & \sigma_2^2(X_2'X_2)^{-1} \end{pmatrix} \right),
\]

(3.18)

and

\[
S_i^2(X_i'X_i)^{-1}
\]

is the random matrix of order \((p \times p)\) for the \( i^{th} \) regime, where (see Appendix A.1)

\[
\frac{(n_i - p)S_i^2}{\hat{\sigma}_i^2} \sim \chi_{n_i - p}^2.
\]

(3.19)

We would like to test

\( H_0 : \beta_1 = \beta_2 \) against \( H_1 : \beta_1 \neq \beta_2 \).

Suppose the observed value of \( S_i^2 \) is \( s_i^2 \). Let us define

\[
Z = \left[ \frac{\sigma_1^2(X_1'X_1)^{-1} + \sigma_2^2(X_2'X_2)^{-1}}{[b_1 - b_2] - (\beta_1 - \beta_2)] \right]^{-1/2}.
\]
Chapter 3. Generalized Inference for Multiple Linear Regression Parameters

and

\[ U = \frac{s_1^2}{\sigma_1^2} \times (X_1'X_1)^{-1} + \frac{s_2^2}{\sigma_2^2} \times (X_2'X_2)^{-1}. \]

From (3.18),

\[ Z \sim N_p(0, I). \]

The matrix \( U \) can be rewritten as

\[ U = \frac{s_1^2}{\sigma_1^2} \times (X_1'X_1)^{-1} + \frac{s_2^2}{\sigma_2^2} \times (X_2'X_2)^{-1}, \]

and then, from (3.19),

\[ U = \frac{(n_1 - p)s_1^2}{\chi_{n_1-p}^2} \times (X_1'X_1)^{-1} + \frac{(n_2 - p)s_2^2}{\chi_{n_2-p}^2} \times (X_2'X_2)^{-1}. \]

Now, define

\[ T_I = Z'UZ = Z' \left( \frac{(n_1 - p)s_1^2}{\chi_{n_1-p}^2} \times (X_1'X_1)^{-1} + \frac{(n_2 - p)s_2^2}{\chi_{n_2-p}^2} \times (X_2'X_2)^{-1} \right) Z. \] (3.20)

Clearly the distribution of \( T_I \) is independent of any unknown parameters. Further, for given \( y \), the observed value of \( T_I \) is

\[ t_I = \left[ (b_1 - b_2) - (\beta_1 - \beta_2) \right]' u^{-1/2} uu^{-1/2} \left[ (b_1 - b_2) - (\beta_1 - \beta_2) \right] \]

\[ = \left[ (b_1 - b_2) - (\beta_1 - \beta_2) \right]' \left[ (b_1 - b_2) - (\beta_1 - \beta_2) \right], \]

where

\[ u = \left[ \sigma_1^2 (X_1'X_1)^{-1} + \sigma_2^2 (X_2'X_2)^{-1} \right] \]

is the observed value of \( U \). Under \( H_0 \) the observed value of \( T_I \) does not depend on any unknown parameters. Further, for given \( y \), \( t_I \) is a positive definite quadratic form in \[ (b_1 - b_2) - (\beta_1 - \beta_2) \]. Therefore, \( t_I \) is a non-decreasing function of \( \beta_1 - \beta_2 \). It implies that \( P(T_I \geq t_I) \) is stochastically non-increasing in \( \beta_1 - \beta_2 \). Thus, \( T_I \) is a generalized test variable. The generalized p-value is

\[ P(T_I \geq t_I \mid H_0). \] (3.21)
Now, we will construct generalized confidence region for $\beta_1 - \beta_2$ based on the distribution of the generalized test variable $T_I$. Let $t_{I_{1-\gamma}}$ satisfy that

$$P(T_I \leq t_{I_{1-\gamma}}) = 1 - \gamma.$$  

Then, a $100(1 - \gamma)$ percent generalized confidence region for the elements of $\beta_1 - \beta_2$ is represented by the set of values of the vector $b_1 - b_2$ which satisfy the following inequality

$$[(b_1 - b_2) - (\beta_1 - \beta_2)]' [(b_1 - b_2) - (\beta_1 - \beta_2)] \leq t_{I_{1-\gamma}}.$$  \hspace{1cm} (3.22)

In testing the hypothesis

$$H_0 : \beta_{1k} = \beta_{2k} \text{ against } H_1 : \beta_{1k} \neq \beta_{2k}, \quad k = 1, 2, \ldots, p,$$

we use the GPQ for $\beta_{1k} - \beta_{2k}$ as we did for the simple linear regression model. The GPQ for $\beta_{1k} - \beta_{2k}$, denoted by $R_{\beta_{1k}-\beta_{2k}}$, is simply an extension of GPQs given in (2.20) and (2.22). Now,

$$R_{\beta_{1k}-\beta_{2k}} = \left. \begin{array}{c} b_{1k}(X_1, y_1) - b_{2k}(X_2, y_2) - T_{n_1+n_2-2p} \\ \times \left( \frac{1}{n_1+n_2-2p} \left( \frac{(n_1-p)s_1^2d_{1kk}}{B} + \frac{(n_2-p)s_2^2d_{2kk}}{1-B} \right) \right)^{1/2} \end{array} \right\} \hspace{1cm} (3.23)$$

where $s_i^2$ is the observed value of $S_i^2 = \text{error mean square for regime } i$, $S_i^2d_{ikk}$ is an unbiased estimator of the variance of $b_{ik}$ and

$$B = \frac{\chi^2_{n_1-p} \chi^2_{n_2-p}}{\chi^2_{n_1} + \chi^2_{n_2}} \sim Beta \left( \frac{n_1-p}{2}, \frac{n_2-p}{2} \right).$$

A joint $100(1 - \alpha)$ percent generalized confidence interval for $\beta_{1k} - \beta_{2k}$, $k = 1, 2, \ldots, p$, is obtained by computing individual generalized confidence interval for $\beta_{1k} - \beta_{2k}$ each with confidence coefficient $(1 - \alpha/p)$ through simulation.
Chapter 4

Simulation Study

Simulation was carried out to study the performance of generalized confidence intervals (GCIs) of linear regression coefficients and dispersion parameters and generalized tests (GTs) for comparing regression coefficients for small and moderate sample sizes 3, 5, 10, 14, 15, 20, 30 and 60. Independent variables $X$ were considered non-stochastic but different assumptions about the error distribution were made. For a fixed sample size, 10,000 samples were generated and the GCIs with typical 95 percent confidence level were computed for each sample. The percentage of intervals that included the true parameter was then obtained. For GTs, generalized p-value was computed for each sample and then the proportion of rejecting null hypothesis was computed under null and alternative hypothesis. In section 4.1, results are presented for simple linear regression models and in section 4.2 results are given for the multivariate case. The programs were written in R to run the simulation.

4.1 Simulation result for simple linear regression model

Consider a simple linear regression model of the form

$$Y_i = \beta_0 + \beta_1 X_i + \varepsilon_i, \ i = 1, 2, ..., n$$

with $X$ fixed and independent normal $\varepsilon_i$'s.
For the classical case when $\varepsilon_i \sim N(0, \sigma^2)$, we generated the observations $y$’s for fixed $X$’s and different set of values of $\beta_0$, $\beta_1$ and $\sigma^2$. The values of $X$ were randomly selected from numbers 1 to 1000 and then those were fixed for the simulation study. Parameter values are presented in Table 3.2. GCIs for $\beta_0$, $\beta_1$ and $\sigma^2$ were computed using (2.3), (2.2) and (2.4), respectively, for each sample obtained from the simulation scheme. Table 4.2 gives the percentages of GCIs that include the true parameter. For each parameter, the observed confidence level for GCI is close to the nominal 95 percent level even for small sample of size 3.

In case of heteroscedasticity $\varepsilon_i \sim N(0, \sigma_i^2)$, we assumed $\sigma_i^2 = \sigma^2 X_i^2$. We used the same set of values of $\beta_0$, $\beta_1$ and $\sigma^2$ for simulation as in the earlier case. The GCIs for $\beta_0$, $\beta_1$ and $\sigma^2$ were obtained using (2.7), (2.8) and (2.9) respectively. Observed confidence levels are presented in Table 4.3 for each parameter. As in the previous case, the observed confidence level for each parameter is close to the nominal 95 percent level.

In situations when the data were collected over two different regimes and error variance remained stationary within each regime but varied between regimes, we fixed the error variance for the first regime to be $\sigma_1^2 = 4$ and for the second regime to be $\sigma_2^2 = 9$. We also assumed that regime change did not affect the regression parameters and we kept their values at $\beta_0 = 5$ and $\beta_1 = 2$. Then GCIs of the regression parameters were computed when:

i. $\sigma_1^2$ and $\sigma_2^2$ were assumed known,

ii. $\sigma_1^2$ and $\sigma_2^2$ were assumed unknown and estimated by the error mean square of the respective regime.

When variances were unknown, the GCIs of the regression parameters were obtained using the proposed weighted generalized pivotal quantities (GPQs) given in (2.14) and (2.15). Then the observed confidence levels of GCIs were calculated.

Tables 4.4 and 4.5 give the simulation results for the two cases where $n_1$ and $n_2$
are the sample sizes of regime 1 and 2 respectively. In the known variance case, the observed confidence levels of GCIs of the regression coefficients are close to the nominal 95 percent level even when the regime sample sizes are small (Table 4.4). Sample size difference of regimes has no impact in observed confidence levels.

When the regimes’ error variances are unknown, we observed that empirical confidence levels are just below the typical 95 percent for overall sample size $n = n_1 + n_2 \leq 20$ (Table 4.5). When $n$ is 14, the observed confidence level of GCIs of the slope parameter is 94 percent for both equal and unequal sample sizes. Increments in sample sizes ($n > 20$) improve the confidence levels close to the nominal level.

In testing the hypothesis of equality of regression coefficients in the two regimes, we proposed the generalized pivotal quantities of their differences in (2.19) and (2.21). The null and alternative hypotheses are

$$H_{01} : \beta_{10} = \beta_{20} \text{ against } H_{11} : \beta_{10} \neq \beta_{20} \text{ and}$$

$$H_{02} : \beta_{11} = \beta_{21} \text{ against } H_{12} : \beta_{11} \neq \beta_{21}.$$  

For this simulation study, we set $\beta_{10} = \beta_{20} = 5$ and $\beta_{11} = \beta_{21} = 2$. We estimated the proposed generalized confidence intervals (GCIs) as well as the classical confidence intervals (CI) for $\beta_{10} - \beta_{20}$ and $\beta_{11} - \beta_{21}$ for each sample obtained from the simulation scheme in homoscedastic and heteroscedastic settings. In the homoscedastic case, the classical confidence intervals were obtained using the exact $t$ distributions each with $n_1 + n_2 - 4$ degrees of freedom. In the heteroscedastic case, the confidence intervals were obtained using approximate $t$ distributions (Schechtman and Sherman; 2007). The approximate $t$ statistic for comparing the slope parameters is

$$t = \frac{b_{11}(X_1, Y_1) - b_{21}(X_2, Y_2) - (\beta_{11} - \beta_{21})}{(S_1^2 f^*(X_1) + S_2^2 f^*(X_2))^{1/2}},$$

where $S_1^2$ and $S_2^2$ are the error mean squares of the two regimes and

$$f^*(X) = \frac{1}{\sum (X_i - \bar{X})^2}.$$
The degrees freedom of this $t$ statistic is obtained by applying the Satterthwaite’s approximation (Satterthwaite; 1941) which is

$$r = \frac{(S_1^2 f^*(X_1) + S_2^2 f^*(X_2))^2}{\left(\frac{(S_1^2 f^*(X_1))^2}{n_1 - 2} + \frac{(S_2^2 f^*(X_2))^2}{n_2 - 2}\right)}.$$

Similarly, the approximate $t$ statistic can be obtained for comparing the intercepts of the two regimes. Then, we computed the percentages of times we rejected the null hypothesis for the generalized and classical tests and compare these values with the nominal value of 5 percent. In the case of homoscedasticity, we set $\sigma_1^2 = \sigma_2^2 = 4$. For heteroscedasticity, we considered two situations:

i. moderate heteroscedasticity ($\sigma_1^2 = 4$ and $\sigma_2^2 = 9$) and

ii. severe heteroscedasticity ($\sigma_1^2 = 4$ and $\sigma_2^2 = 25$).

Tables 4.6 and 4.7 give the simulation results. In the case of homoscedasticity, the test is found to be conservative for small samples ($n \leq 14$). As sample size increases, the test attains the nominal significance level of 0.05 for $n \geq 20$. In contrast, the classical test preserves the nominal level for all sample sizes considered. No impact on the significance levels was observed due to the sample size differences of regimes.

In the case of moderate heteroscedasticity, we observed that when the regimes’ sample sizes are equal, the significance levels of the proposed generalized tests are close to the nominal 0.05 level for $n \geq 14$. For $n = 14$ ($n_1 = 7$ and $n_2 = 7$), the observed significance level of the test is 0.04 for comparing the slopes of the two regimes. When the regimes’ sample sizes are unequal, the test is found to be conservative if overall sample size is small ($\leq 14$) and there exists large difference in regimes’ sample sizes. When regimes’ sample sizes are 4 and 10, the observed significance level of the test is 0.02 for comparing the slope. As sample size increases, the test preserves the significance levels close to the nominal level for $n \geq 20$. On the other hand, in the case of moderate heteroscedasticity, the classical test based on the equal variance assumption gives significance level close to the nominal level when the regimes’ sample sizes are equal. When regimes’ sample sizes are unequal, the classical
test is either too conservative or too liberal. The classical test is found to be liberal when the large sample has smaller error variance than that of the small sample and is found to be conservative in the opposite case. Even when overall sample size is large ($\geq 30$), the classical test is conservative if the regimes’ sample sizes differ significantly unlike the proposed test.

In the severe heteroscedastic case, the similar results are obtained for the generalized test as in the case of moderate heteroscedasticity. But the classical test is found to be conservative or liberal in most of the cases of the severe heteroscedasticity, except when the overall sample size is large ($n \geq 30$) and the regimes’ sample sizes are approximately equal. In the heteroscedastic cases, when there is difference in regimes’ sample sizes, the generalized test is comparatively better than the classical test in terms of empirical significance level.

Table 4.8 gives the observed significance levels of the proposed generalized test and the test based on approximate $t$ distributions in testing equality of the regression coefficients in the two regimes in the moderate and severe heteroscedastic cases. We observed that the approximate $t$ test preserves the nominal 5 percent significance level for all sample sizes considered in the heteroscedastic cases.

The powers of the generalized test and the classical test in testing equality of the slope parameters of the two regimes in the heteroscedastic cases are presented in Table 4.9. Figures 4.1 and 4.2 show the power curves of the two tests in testing equality of the slope parameters of the two regimes with severe heteroscedasticity ($\sigma_1^2 = 4$, $\sigma_2^2 = 25$) for different sample sizes, respectively. We observed that the generalized test gives higher power for overall sample size $n \geq 14$. In particular, Figure 4.3 illustrates the behaviour of the power of both tests in the severe heteroscedastic case for $n = 20$ and it is clear that the proposed test performs better than the classical test. In the case of moderate heteroscedasticity, both tests yield similar power for $n \geq 20$.

The size and power of the proposed test and the test based on approximate $t$ in testing equality of the slope parameters in heteroscedastic cases (from moderate to
severe) are presented in Table 4.10 for \( n_1 = 15 \) and \( n_2 = 5 \). Here, fixed \( X \) values considered in simulation are 10, 10.5, 11,..., 17 for regime 1 and 10, 10.5, 11,..., 12 for regime 2. We observed that the size and the power of the generalized test are comparable with that of the approximate \( t \) test. The observed level of significance (size) of the generalized test is close to the nominal 5 percent level for the moderate and the severe heteroscedastic cases. When the slope difference is 8, the power of the generalized test is 1 for the moderate heteroscedasticity \( (\sigma_1^2 = 1, \sigma_2^2 = 2) \) and it is 0.98 for the severe heteroscedasticity \( (\sigma_1^2 = 1, \sigma_2^2 = 4) \). In the extreme case when \( \sigma_1^2 = 1, \sigma_2^2 = 8 \), the power is 0.838 that is also quite satisfactory.
### Table 4.1: Fixed X values for different sample sizes

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Table 4.2: Empirical confidence levels for 95% generalized confidence intervals of the classical linear regression parameters

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Table 4.3: Observed confidence levels for 95% generalized confidence intervals of the classical linear regression parameters in the case of heteroscedasticity

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Table 4.4: Observed confidence levels for 95% generalized confidence intervals of the simple linear regression coefficients when error variances $\sigma_1^2 = 4$ and $\sigma_2^2 = 9$ of the two regimes are assumed known

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Table 4.5: Observed confidence levels for 95% generalized confidence intervals of the simple linear regression coefficients when error variances $\sigma_1^2 = 4$ and $\sigma_2^2 = 9$ of the two regimes are assumed unknown.

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Table 4.6: Observed significance levels of the generalized and classical test in testing the equality of the regression coefficients in homoscedastic case ($\sigma_1^2 = \sigma_2^2 = 4$) at 0.05 level of significance

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Table 4.7: Observed significance levels of the generalized and classical tests in testing the equality of the regression coefficients in heteroscedastic cases at 0.05 level of significance

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Table 4.8: Observed significance levels of the generalized test and the test based on approximate t distribution in testing the equality of the regression coefficients in heteroscedastic cases at 0.05 level of significance

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Table 4.9: Power of the tests in testing the equality of the slope parameters ($\beta_{11} = \beta_{21} = 2$) in the two regimes with heteroscedasticity at 0.05 level of significance

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Table 4.10: Size and power of the generalized test and the test based on approximate $t$ in testing the equality of the slope parameters ($\beta_{11} - \beta_{21} = 0$) in the two regimes of sample sizes $n_1 = 15$ and $n_2 = 5$ in heteroscedastic cases at 0.05 level of significance

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Figure 4.1: Power of the generalized test at 0.05 level of significance in testing the equality of the slope parameters ($\beta_{11} = \beta_{12}$) in the two regimes with severe heteroscedasticity $\sigma_1^2 = 4$ and $\sigma_2^2 = 25$ for different sample sizes
Figure 4.2: Power of the classical test based on the equal variance assumption in testing the equality of the slope parameters ($\beta_{11} = \beta_{12}$) in the two regimes with severe heteroscedasticity $\sigma_1^2 = 4$ and $\sigma_2^2 = 25$ for different sample sizes at 0.05 level of significance.
Figure 4.3: Power of the generalized and classical tests in testing the equality of the slope parameters ($\beta_{11} = \beta_{12}$) in the two regimes with severe heteroscedasticity $\sigma_1^2 = 4$ and $\sigma_2^2 = 25$ for overall sample size 20 ($n_1 = 8$ and $n_2 = 12$) at 0.05 level of significance
4.2 Simulation result for multiple linear regression model

Consider the regression models of two regimes

\[
\begin{align*}
Y_{1j} &= \beta_{10} + \beta_{11}X_{11j} + \beta_{12}X_{12j} + \varepsilon_{1j}, \ j = 1, 2, \ldots, n_1, \\
Y_{2j} &= \beta_{20} + \beta_{21}X_{21j} + \beta_{22}X_{22j} + \varepsilon_{2j}, \ j = 1, 2, \ldots, n_2,
\end{align*}
\]

where \(\varepsilon_{1j} \sim iid \ N(0, \sigma^2_1)\) and \(\varepsilon_{2j} \sim iid \ N(0, \sigma^2_2)\). In matrix notation

\[
\begin{align*}
Y_1 &= X_1\beta_1 + \varepsilon_1, \\
Y_2 &= X_2\beta_2 + \varepsilon_2,
\end{align*}
\]

where \(\beta_i = (\beta_{i0}, \beta_{i1}, \beta_{i2})'\),

\(\varepsilon_i = (\varepsilon_{i1}, \varepsilon_{i2}, \ldots, \varepsilon_{in_i})' \sim N_{n_i}(0, \sigma^2_{i}I_{n_i})\),

\(\varepsilon_1\) and \(\varepsilon_2\) are independent,

\(Y_i = (Y_{i1}, Y_{i2}, \ldots, Y_{in_i})'\) and

\(X_i\) is the design matrix of order \((n_i \times 3)\) for the \(i^{th}\) regime.

To test the hypothesis

\[H_0 : \beta_1 = \beta_2 \text{ against } H_1 : \beta_1 \neq \beta_2,\]

we proposed a generalized test variable in (3.20). Simulation was done to obtain the empirical significance level and the power of the test at 0.05 level of significance for regimes’ sample sizes 5, 10 and 15. The explanatory variables were considered fixed. The values of \(X_{i1}\) were obtained from a sequence starting from 1 and then increased by 5 at every step. The values of \(X_{i2}\) were randomly sampled from 1000 to 10000 and then they were fixed for the simulation. In table 4.11, these \(X\) values are given. For heteroscedasticity, three situations were considered:

i. moderate heteroscedasticity \((\sigma^2_1 = 1 \text{ and } \sigma^2_2 = 2)\),

ii. severe heteroscedasticity \((\sigma^2_1 = 1 \text{ and } \sigma^2_2 = 4)\) and

iii. extreme heteroscedasticity \((\sigma^2_1 = 1 \text{ and } \sigma^2_2 = 8)\).
Observations $y$'s were generated using (4.1) for $\beta_0 = 5, \beta_{i1} = 0.5$ and $\beta_{i2} = 1$. For a fixed sample size, 10,000 samples were generated and for each sample the generalized p-value for the test was computed using (3.21). Then proportion of rejecting the null hypothesis was calculated. This gives the empirical significance level for the generalized test. The power of the test was obtained by assigning the difference between corresponding regression coefficients $\beta_{1k} - \beta_{2k} \neq 0, k=1,2,3$ following the same procedure.

Empirical significance levels of the proposed generalized test at 0.05 level are given in Table 4.12 for the different sample sizes and the heteroscedastic cases. When the regimes’ sample sizes are 15 and 5, the observed significance level of the test is 0.045 in the case of moderate heteroscedasticity. In the cases of the severe and extreme heteroscedasticity, the observed levels are 0.048 and 0.041, respectively. When regimes’ sample sizes are 15 and 10, the empirical significance levels of the test are 0.052, 0.049 and 0.047 for moderate to extreme heteroscedastic cases, respectively. For equal sample case ($n_1 = n_2 = 15$), the similar results are observed. Thus for small samples and in the heteroscedastic cases the test preserves the significance level very close to the nominal 0.05 level.

In Table 4.13, the power of the generalized test is given for regimes’ sample sizes 15 and 5 and in the heteroscedastic cases at 0.05 level of significance. We observed that when the difference between the sets of regression coefficients is $\beta_1 - \beta_2 = (20, 10, 15)'$, the power of the test is 0.91 in the moderate heteroscedastic case. When the difference is increased to $(30, 15, 20)'$, the power of the test is 0.996 in the moderate heteroscedastic case and it is 0.915 in the severe heteroscedastic case. In the case of extreme heteroscedasticity, a large difference in the sets of regression coefficients is expected. We observed that in the extreme heteroscedastic case when the difference between the coefficients is large $(30, 20, 25)'$, the power of the test is 0.800, which is also quite satisfactory. Therefore, the proposed generalized test maintains good power in testing equality of the two sets of regression coefficients of the two regimes in the heteroscedastic cases.
Table 4.11: Fixed X values for different sample sizes

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Table 4.12: Observed significance levels of the generalized test (GT) in testing the equality of the two sets of regression coefficients in the two regimes with heteroscedasticity at 0.05 level of significance

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Table 4.13: Power of the generalized test (GT) in testing the equality of the two sets of regression coefficients in the two regimes of sample sizes $n_1 = 15$ and $n_2 = 5$ with heteroscedasticity at 0.05 level of significance

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<td>1</td>
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<td>0.998</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>4</td>
<td>0.964</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>8</td>
<td>0.800</td>
</tr>
</tbody>
</table>
4.3 Conclusion

In situations when the data were collected over two different regimes and the regression coefficients remained the same between regimes only the error variance varied by regimes, we proposed generalized confidence intervals (GCIs) for the regression coefficients. The simulation study shows that the GCIs preserve the confidence levels close to the nominal level. In testing equality of the regression coefficients in the two regimes, the generalized pivotal quantities of their differences and the generalized p-values were developed. When the regimes’ error variances are different, the testing problem becomes a Behrens-Fisher problem in regression setting. In such case, the generalized test is comparatively better than the classical test based on equal variance assumption when regimes’ sample sizes are unequal. The generalized test is found comparable with the test based on approximate $t$ distribution in the heteroscedastic cases. Generalized methods are especially useful in multiparameter cases where nontrivial tests are difficult to obtain. To test the equality of the sets regression coefficients of two regimes under heteroscedasticity, we proposed a generalized test. The test preserves the nominal significance level and maintain satisfactory power.
Chapter 5

Application of Proposed Generalized Methods on Real Data

In this section, we applied the proposed methods on two data sets: the community health study data of Sarnia in 2005 and the US gasoline consumption data before and after the 1973 oil crisis. The programs were written in R and the statistical package SPSS was used in the data analyses.

5.1 Is air pollution in Sarnia causing respiratory problems among adults?

Sarnia is a major city in Southwestern Ontario, Canada. The city is also known as ‘Chemical Valley’ because over 40 percent of Canada’s chemical industries are there. Toxic releases of those industries pollute the environment of the city and put the residents’ life at risk of developing different diseases. The pollutants include respiratory toxicant, lead, mercury, benzene and nickel (Fung et al; 2007). Our objective is to examine whether the pollution has any impact on chronic respiratory problems. A community health study was conducted in the city in 2005. Residents of age 18 years or older were interviewed. A predesigned questionnaire was used in the survey. Most of the questions were about the mental and physical health of the
respondents. Besides, they recorded responses such as length of stay in the region, presence in the region in the summer period, smoke, odours of the chemical plants etc. that can be used as a proxy for the exposure to the environment. Socio-demographic information of the residents was also documented.

5.1.1 Description of the data

The data were collected from the 5 regions of the city with postal codes N7S, N7T, N7V, N7W and N7X. The number of respondents interviewed from these regions are 268, 392, 120, 16, and 8, respectively. For each respondent the number of respiratory problems was counted. The respiratory problems included hay fever or other allergies, an attack of shortness of breath at any time in the last 12 months, an asthmatic attack in the last 12 months, current asthma and other respiratory problems. A respondent’s length of stay in the community in completed years was recorded. It can be a proxy for the length of exposure to pollutions in Sarnia. Age of the respondent was categorized as 18-40 years and 40+, as older people are more vulnerable of developing health problems.

5.1.2 Analysis results

The scatter plot of the years of living in Sarnia and the number of respiratory problems (Figure 5.1) does not show a clear picture of relationship between them. Respondents were then grouped according to their length of stay and the mean of the number of respiratory problems was computed for each group. Figure 5.2 gives the scatter plot of the years of living in Sarnia and the mean number of respiratory problems for the five regions. A pattern of relationship emerges. If we discard the groups that have no respiratory problems from the analysis, a linear trend may exist (Figure 5.3). In this case the correlation coefficient is significant \( r = 0.264 \), \( p \) - value = 0.001. We fitted a simple linear regression model with mean number of respiratory problems as response and years of living as regressor. Note that the data had been aggregated by regions and years of living and the model was fitted using the aggregated data. Table 5.1
Chapter 5. Application of Proposed Generalized Methods on Real Data

gives analysis of variance for the model. Estimates with their 95 percent generalized confidence intervals (GCIs) and generalized p-values (GP-values) are given in Table 5.2. We observed that years of living in Sarnia is a significant regressor of mean number of respiratory problems. This gives an indication that long term exposure to the environmental pollution in Sarnia may create respiratory health hazard.

Since the data were collected from 5 different regions of Sarnia, we further examined whether the relationship holds in each region. Table 5.3 gives the correlation between years of living and mean number of respiratory problems by region. The significant relationship is observed only in region N7S. It is to be noted that in region N7X none had any respiratory problems. The estimates of the parameters for simple linear regression model with their corresponding GCIs (95 percent) and GP-values by region are given in Table 5.4. We observed that years of living is a significant regressor for mean number of respiratory problems in region N7S.

To illustrate our proposed generalized method for comparing two corresponding regression coefficients, we considered region N7S as regime 1 and N7T as regime 2. Table 5.5 presents the 95 percent GCIs for the differences of the regression coefficients with GP-values. It is shown that years of living in Sarnia has a significant different effect on the mean number of respiratory problems in region N7S from that of region N7T.

One might argue that the observed positive relationship between years of living in Sarnia and mean number of respiratory problems is due to the respondent’s age. We controlled the effect of age by fitting a multiple linear regression model of mean number or respiratory problems on years of living and age of respondents. Here, the second stage of aggregation was done on the data. The data had been aggregated by region, years of living and age of the respondent. The analysis results are given in Table 5.6 and 5.7. We observed that the positive relationship between years of living in Sarnia and mean number of respiratory problems still holds at $\alpha = 0.05$. 
5.1.3 Conclusion

Continuous disposal of industrial toxicant made the environment of Sarnia polluted and put the residents’ lives at risk. Surveys are needed to measure the extent of pollution and it’s impact on human lives and environment. Measures should also be taken to recycle the industrial waste.
Figure 5.1: The scatter plot of the years of living in Sarnia and the number of respiratory problems
Figure 5.2: The scatter plot of the years of living and the mean number of respiratory problems for the five regions in Sarnia
Figure 5.3: The scatter plot of the years of living and the mean number of respiratory problems for the five regions in Sarnia after excluding groups with no respiratory problems
Chapter 5. Application of Proposed Generalized Methods on Real Data

Table 5.1: Analysis of variance for the linear regression model of mean number of respiratory problems on years of living in Sarnia

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Sum of squares</th>
<th>df</th>
<th>Mean square</th>
<th>F</th>
<th>Sig</th>
</tr>
</thead>
<tbody>
<tr>
<td>Years of living</td>
<td>5.466</td>
<td>1</td>
<td>5.466</td>
<td>11.893</td>
<td>0.001</td>
</tr>
<tr>
<td>Residual</td>
<td>73.069</td>
<td>159</td>
<td>0.460</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>78.535</td>
<td>160</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.2: Estimates of the parameters for the linear regression model of mean number of respiratory problems on years of living in Sarnia

<table>
<thead>
<tr>
<th>Variables in the model</th>
<th>Estimate</th>
<th>95% GCI</th>
<th>GP-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.684</td>
<td>(0.485, 0.882)</td>
<td>0.000</td>
</tr>
<tr>
<td>Years of living</td>
<td>0.008</td>
<td>(0.004, 0.013)</td>
<td>0.001</td>
</tr>
</tbody>
</table>
Table 5.3: the Correlation coefficient between years of living in Sarnia and the mean number of respiratory problems by region

<table>
<thead>
<tr>
<th>Region</th>
<th>r</th>
<th>p-value</th>
<th>sample size</th>
</tr>
</thead>
<tbody>
<tr>
<td>N7S</td>
<td>0.412</td>
<td>0.001</td>
<td>58</td>
</tr>
<tr>
<td>N7T</td>
<td>0.085</td>
<td>0.509</td>
<td>63</td>
</tr>
<tr>
<td>N7V</td>
<td>0.279</td>
<td>0.105</td>
<td>35</td>
</tr>
<tr>
<td>N7W</td>
<td>0.779</td>
<td>0.121</td>
<td>5</td>
</tr>
<tr>
<td>N7X</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 5.4: Estimates of the parameters for the linear regression model of mean number of respiratory problems on years of living in Sarnia by region

<table>
<thead>
<tr>
<th>Region</th>
<th>Variable</th>
<th>Parameters</th>
<th>Estimates</th>
<th>95% GCI</th>
<th>GP-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>N7S</td>
<td>Intercept</td>
<td>$\beta_{10}$</td>
<td>0.538</td>
<td>(0.224, 0.852)</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>Years of living</td>
<td>$\beta_{11}$</td>
<td>0.013</td>
<td>(0.005, 0.021)</td>
<td>0.001</td>
</tr>
<tr>
<td>N7T</td>
<td>Intercept</td>
<td>$\beta_{20}$</td>
<td>0.801</td>
<td>(0.506, 1.095)</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>Years of living</td>
<td>$\beta_{21}$</td>
<td>0.002</td>
<td>(-0.005, 0.009)</td>
<td>0.509</td>
</tr>
<tr>
<td>N7V</td>
<td>Intercept</td>
<td>$\beta_{30}$</td>
<td>0.659</td>
<td>(0.135, 1.182)</td>
<td>0.015</td>
</tr>
<tr>
<td></td>
<td>Years of living</td>
<td>$\beta_{31}$</td>
<td>0.010</td>
<td>(-0.002, 0.023)</td>
<td>0.105</td>
</tr>
<tr>
<td>N7W</td>
<td>Intercept</td>
<td>$\beta_{40}$</td>
<td>0.977</td>
<td>(-0.493, 2.447)</td>
<td>0.125</td>
</tr>
<tr>
<td></td>
<td>Years of living</td>
<td>$\beta_{41}$</td>
<td>0.026</td>
<td>(-0.012, 0.630)</td>
<td>0.121</td>
</tr>
</tbody>
</table>

Table 5.5: The 95 percent Generalized confidence intervals for the difference of the regression coefficients in regions N7S and N7T

<table>
<thead>
<tr>
<th>Difference of the parameters</th>
<th>GCI</th>
<th>GP-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_{10} - \beta_{20}$</td>
<td>(-0.694, 0.163)</td>
<td>0.228</td>
</tr>
<tr>
<td>$\beta_{11} - \beta_{21}$</td>
<td>(0.0004, 0.021)</td>
<td>0.039</td>
</tr>
</tbody>
</table>
Table 5.6: Analysis of variance for the linear regression model of mean number of respiratory problems on years of living in Sarnia and age of respondents

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Sum of squares</th>
<th>df</th>
<th>Mean square</th>
<th>F</th>
<th>Sig</th>
</tr>
</thead>
<tbody>
<tr>
<td>Years of living</td>
<td>3.369</td>
<td>1</td>
<td>3.369</td>
<td>7.122</td>
<td>0.008</td>
</tr>
<tr>
<td>Age of respondents</td>
<td>0.269</td>
<td>1</td>
<td>0.269</td>
<td>0.569</td>
<td>0.452</td>
</tr>
<tr>
<td>Residual</td>
<td>90.396</td>
<td>191</td>
<td>0.473</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>94.034</td>
<td>193</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.7: Estimates of the parameters for the linear regression model of mean number of respiratory problems on years of living in Sarnia and age of respondents

<table>
<thead>
<tr>
<th>Variables in the model</th>
<th>Estimate</th>
<th>95%GCI</th>
<th>GP-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.836</td>
<td>(0.637, 1.035)</td>
<td>0.000</td>
</tr>
<tr>
<td>Years of living</td>
<td>0.007</td>
<td>(0.002, 0.012)</td>
<td>0.008</td>
</tr>
<tr>
<td>Age category</td>
<td>-0.049</td>
<td>(-0.280, 0.181)</td>
<td>0.673</td>
</tr>
</tbody>
</table>
5.2 Impact of gasoline price on total US gasoline consumption before and after 1973 oil crisis

The Oil crisis began when members of the Organization of the Petroleum Exporting Countries (OPEC) with Egypt and Syria placed an oil embargo on the United States on October 15, 1973. This came as a punishment for the US decision to resupply the Israeli military during the October War, the fourth Arab-Israeli war. The embargo caused a persistent effect in the US economy because the industrialized US economy was heavily dependent on the crude oil and OPEC was their predominant supplier.

Here we studied the US gasoline consumption data from 1960 to 1995. We fitted a linear regression model to the data. Then we divided the data into two regimes: before 1973 as regime 1 and on or after 1973 as regime 2 and examined using our proposed generalized test variable whether the set of regression coefficients of the regime 1 model is different from that of regime 2 model.

5.2.1 Description of the data

The data were taken from the Council of Economic Advisers, Report of the President 1996 (http://pages.stern.nyu.edu/~wgreene/Text/tables/TableF2-2.txt). The data consist of total US gasoline consumption (expenditure/price index), price index for gasoline, percapita disposable income, price index for new cars, price index for used cars, price index for public transport, aggregate price index for consumer durables, aggregate price index for consumer non-durables, aggregate price index for consumer services, and US total population.

5.2.2 Analysis results

A linear regression model was selected using stepwise selection criteria taking total US gasoline consumption as the response variable and all the remaining variables as the regressors. Collinearity among the independent variables (Myers; 1990) was also taken care in the model selection. The final model included price index for gasoline
and price index for used cars as the regressors. The overall model fit was good ($R^2 = 0.83$ and $F_{2,32} = 37$ with p-value < 0.001). Table 5.8 presents the estimated regression coefficients with their GCIs and GP-values. Collinearity diagnostics for the model are presented in Table 5.9. We observed that the values of the variance inflation factor are less than 10, none of the condition index is greater than 30 and the smallest eigen value is not close to zero. All these diagnostics indicate that collinearity is not a problem for the model. The normality assumption of the errors was also satisfied ($Shapiro-Wilk W=0.967$, p-value=0.361)

We observed that (Table 5.8) the price index of gasoline is not a significant regressor for total US gasoline consumption for the period of 1960 to 1995. This result is opposite to what we expected. The reason could be that we analyzed the data of two very different economic era, before the 1973 oil crisis and after the crisis, together. Figures 5.4 and 5.5 give the plots of the consumption of gasoline and the price index for gasoline by years, respectively. We observed that before the crisis, there was not that much variation in gasoline price and its consumption increased steadily. But after the crisis, we observed much more variation in gasoline price and its consumption. The scatter plot of the price and consumption of gasoline before and after the oil crisis is given in Figure 5.6. Before the crisis, a positive linear relationship between price and consumption of gasoline was observed. But it might not be the case after the crisis.

Then, we splitted the data in to two regimes: before the oil crisis and on or after the crisis and fitted the model separately for the two regimes. The estimated regression coefficients for the two regimes are given in Table 5.10. We observed that before the oil crisis, the price index of gasoline was positively related with the total consumption of gasoline. Although increase in price index resulted in increase in consumption, it is not surprising, because at the time, price of gasoline was inexpensive. However, between 1973 to 1995, we observed a significant reverse relationship between price index for gasoline and total gasoline consumption. After the oil embargo in 1973, the price of gasoline increased abruptly and became expensive. As a result, increase in
price index resulted in decrease in gasoline consumption.

We observed that the estimated regression coefficients of the two regimes are quite different from each other. Severe heterogeneity in error variances of the two regimes was also observed. Error mean squares for regimes 1 and 2 are 17.416 and 99.56, respectively, that are significantly different ($F_{20,10}=5.717$, p-value=0.004). In such case, we would like to test whether the two sets of regression coefficients are different, i.e.

$$H_0 : \beta_1 = \beta_2 \text{ against } H_1 : \beta_1 \neq \beta_2,$$

where $\beta_i$ is the vector of regression coefficients for the regime $i = 1, 2$. As the sample size of the first regime is small ($n_1 = 13$) and severe heteroscedasticity between two regimes exists, the classical asymptotic test and the Chow test are not appropriate for this case. We applied our proposed generalized test for testing the hypothesis, since the test can be efficiently used for small sample sizes and heteroscedastic case. The observed generalized test variable is 495406.5 with generalized p-value $< 0.0001$. Therefore, at 0.05 level of significance we reject the null hypothesis.

Then, we tested the equality of each of the regression coefficients of regime 1 with the corresponding regression coefficients of regime 2. We constructed the GCIs for the difference of the corresponding regression coefficients of the two regimes and then their GP-values. There are 3 regression coefficients. Therefore, to maintain the global level at least approximately to be 0.05, we construct GCIs each with confidence coefficients $(1 - 0.05/3) \approx 0.98$. Table 4.11 gives the GCIs for the difference of the regression coefficients with their GP-values. We observed that after the oil crisis in 1973, increase in gasoline price resulted in significant decrease in its consumption unlike prior 1973.

5.2.3 Conclusion

When we suspect regime change in the data, analysis should be done by regimes. The equality of the sets of regression parameters of the regimes should be tested. We
applied generalized test that can efficiently test the equality of the sets of regression coefficients of two regimes for all sample sizes and heteroscedastic case.
Figure 5.4: The plot of the consumption of gasoline by years
Figure 5.5: The plot of the price index for gasoline by years
Figure 5.6: The scatter plot of the price and consumption of gasoline before and after the oil crisis.
Table 5.8: Estimates of the parameters for the linear regression model of the total US gasoline consumption on price index for gasoline and price index for used cars during 1960 and 1995

<table>
<thead>
<tr>
<th>Variables in the model</th>
<th>Estimate</th>
<th>95% GCI</th>
<th>GP-value</th>
<th>VIF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>154.42</td>
<td>(133.54, 173.31)</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>Price index for gasoline</td>
<td>4.263</td>
<td>(-14.34, 22.861)</td>
<td>0.644</td>
<td>5.466</td>
</tr>
<tr>
<td>Price index for used cars</td>
<td>26.37</td>
<td>(9.86, 42.88)</td>
<td>0.003</td>
<td>5.466</td>
</tr>
</tbody>
</table>

Table 5.9: Collinearity diagnostics for the linear regression model of the total US gasoline consumption on price index for gasoline (PIG) and price index for used cars (PUC) during 1960 and 1995

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Eigen value</th>
<th>Condition index</th>
<th>Variance proportion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Constant</td>
</tr>
<tr>
<td>1</td>
<td>2.813</td>
<td>1.000</td>
<td>0.02</td>
</tr>
<tr>
<td>2</td>
<td>0.164</td>
<td>4.144</td>
<td>0.91</td>
</tr>
<tr>
<td>3</td>
<td>0.023</td>
<td>11.099</td>
<td>0.06</td>
</tr>
</tbody>
</table>
Table 5.10: Estimates of the parameters for the linear regression model of the total US gasoline consumption on price index for gasoline (PIG) and price index for used cars (PUC) before and after the oil crisis in 1973

<table>
<thead>
<tr>
<th>Regime</th>
<th>Variables</th>
<th>Estimate</th>
<th>95% GCI</th>
<th>GP-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1960-1972</td>
<td>Intercept</td>
<td>-337.03</td>
<td>(-378.68, -295.37)</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>PIG</td>
<td>381.14</td>
<td>(307.10, 455.18)</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>PUC</td>
<td>134.09</td>
<td>(74.04, 194.14)</td>
<td>0.001</td>
</tr>
<tr>
<td>1973-1995</td>
<td>Intercept</td>
<td>232.20</td>
<td>(216.73, 247.67)</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>PIG</td>
<td>-18.66</td>
<td>(-26.36, -10.95)</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>PUC</td>
<td>26.64</td>
<td>(20.80, 32.48)</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Table 5.11: The Generalized confidence intervals for the difference of the corresponding regression coefficients of two regimes each with confidence coefficient 0.98

<table>
<thead>
<tr>
<th>Difference of the parameters</th>
<th>GCI</th>
<th>GP-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_{10} - \beta_{20}$</td>
<td>(-623.6, -514.4)</td>
<td>0.000</td>
</tr>
<tr>
<td>$\beta_{11} - \beta_{21}$</td>
<td>(309.28, 491.9)</td>
<td>0.000</td>
</tr>
<tr>
<td>$\beta_{12} - \beta_{22}$</td>
<td>(31.02, 182.55)</td>
<td>0.003</td>
</tr>
</tbody>
</table>
Chapter 6

Conclusion and Future Research

Weerahandi (1989, 1993) developed the concept of generalized confidence intervals and generalized p-values for complex inference problems involving nuisance parameters. This generalized methodology of inference is suitable for all sample sizes and is found to be efficient even when the assumptions of optimal inference do not hold.

In this thesis we applied the concept to the case of simple and multiple linear regression models. Specifically, we constructed generalized confidence intervals for regression coefficients, dispersion parameters and the expected response for simple and multiple linear regression models. We also constructed generalized confidence regions for multiple linear regression parameters.

The regression data from two different regimes were considered. We considered a particular case when the regression coefficients remained the same for the two regimes and the error variances were assumed same within the regime but different between regimes. We proposed generalized confidence regions and generalized confidence intervals for the regression parameters in such a case. The global confidence level was maintained using the Bonferroni approach. The simulation study showed that the GCIs preserve the confidence levels close to the nominal level for overall sample size \( n = n_1 + n_2 \geq 14 \).

In testing the equality of the regression coefficients in the two regimes, we developed the generalized pivotal quantities of their differences and the generalized p-values. From the simulation study we observed that when the regimes’ error vari-
ances are different, the generalized test is comparatively better than the classical test based on equal variance assumption in the case of unequal regimes’ sample sizes. The test is found comparable with the test based on approximate $t$ distribution in the heteroscedastic cases.

Generalized methods are especially useful in multiparameter cases where nontrivial tests are difficult to obtain. To test the equality of the sets regression coefficients of two regimes under heteroscedasticity, the Chow test was extended by Toyoda (1974). But the test’s significance level is greatly affected if the regimes have small sample sizes. In classical inference, only asymptotic tests are available for this problem. In such a case, we proposed generalized test variables and generalized p-values that can be applied efficiently for all sample sizes and for homoscedastic as well as heteroscedastic cases. The simulation study showed that the proposed method preserves the nominal significance level and provides satisfactory power under heteroscedasticity and for small and moderate sample sizes.

We also constructed the generalized confidence region for the difference of the two sets of regression coefficients and then, the generalized confidence intervals for each elements of that vector.

We applied our proposed methodology on the two data sets: the community health study data of Sarnia in 2005 and the US gasoline consumption data before and after the 1973 oil crisis. These applications clearly showed that there is a regime change in the data. Accordingly, the analysis should be done by regimes.

In this thesis, regressor variables were considered to be non-stochastic. Also, the error distribution was assumed to be normally distributed. For future research, we plan to investigate

1. the general case where independent variables may be stochastic and
2. the complex cases where the normality assumption of the error is not satisfied.
Appendix A

A.1 Distributions of the estimators of the error variance in linear regression

Consider the linear regression model

\[ Y_j = \beta_1 X_{1j} + \beta_2 X_{2j} + \cdots + \beta_p X_{pj} + \varepsilon_j, \quad j = 1, 2, \ldots, n. \]

Here \( Y_j \) is the response variable for the \( j^{th} \) set of values of \((X_1, X_2, \ldots, X_p)\) and \( \varepsilon_j \) is the corresponding random error term. Also, \( \beta_i, \ i = 1, 2, \ldots, p \) represent a total of \( p \) unknown parameters. Defining

\[
Y = \begin{pmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_n \end{pmatrix}, \quad \beta = \begin{pmatrix} \beta_1 \\ \beta_2 \\ \vdots \\ \beta_p \end{pmatrix}, \quad X = \begin{pmatrix} X_{11} & X_{21} & \cdots & X_{p1} \\ X_{12} & X_{22} & \cdots & X_{p2} \\ \vdots & \vdots & \ddots & \vdots \\ X_{1n} & X_{2n} & \cdots & X_{pn} \end{pmatrix} \quad \text{and} \quad \varepsilon = \begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_n \end{pmatrix},
\]

the model can be written in matrix notation as

\[ Y = X\beta + \varepsilon, \]

where \( X \) has full column rank. The ordinary least squares estimator for \( \beta \) is

\[ \hat{\beta} = b = (X'X)^{-1}X'Y, \quad \text{where} \quad b = (b_1, b_2, \ldots, b_p)', \]

and given the normality assumption on \( \varepsilon \sim N_n(0, \sigma^2 I_n) \),

\[ b \sim N_p \left( \beta, \sigma^2 (X'X)^{-1} \right) \quad (A.1) \]
and

\[ Y \sim N_n(X\beta, \sigma^2 I_n). \quad \text{(A.2)} \]

In this thesis we consider two estimators of the error variance \( \sigma^2 \):

\[ S^2 = \frac{(Y - \hat{Y})'(Y - \hat{Y})}{(n - p)} = \frac{(Y - X\hat{\beta})'(Y - X\hat{\beta})}{(n - p)} \]

and

\[ S_Y^2 = \frac{(Y - X\hat{\beta})'(Y - X\hat{\beta})}{n}. \]

The estimator \( S^2 \), the error mean square, is unbiased and the estimator \( S_Y^2 \), the maximum likelihood estimator, is biased. We are to find the distributions of these two estimators. From (A.2),

\[ \frac{Y}{\sigma} \sim N_n \left( \frac{X\beta}{\sigma}, I_n \right). \]

Let us define

\[ W = \frac{Y - X\hat{\beta}}{\sigma}. \]

Then,

\[ \left( \frac{Y - X\hat{\beta}}{\sigma} \right)' \left( \frac{Y - X\hat{\beta}}{\sigma} \right) = \frac{1}{\sigma^2} (Y - X\hat{\beta})'(Y - X\hat{\beta}). \quad \text{(A.3)} \]

Since

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

where

\[ \left[ I - X(X'X)^{-1}X' \right] Y \]

is an idempotent matrix, from (A.3) we have

\[ \frac{1}{\sigma^2} (Y - X\hat{\beta})'(Y - X\hat{\beta}) = \frac{1}{\sigma^2} Y' \left[ I - X(X'X)^{-1}X' \right] Y, \]

or,

\[ \frac{1}{\sigma^2} (Y - X\hat{\beta})'(Y - X\hat{\beta}) = \left( \frac{Y}{\sigma} \right)' \left[ I - X(X'X)^{-1}X' \right] \left( \frac{Y}{\sigma} \right). \quad \text{(A.4)} \]
Recall that if \( X \sim N_n(\mu, \Sigma) \) where \( \Sigma \) is positive definite, then

\[ X'AX \sim \chi^2_{\text{rank}(A)}(\mu'\mu) \]

iff \( \Sigma A \) is idempotent. Further, \( \text{rank}(A) = \text{trace}(\Sigma A) \).

Therefore, from (A.4),

\[ \frac{1}{\sigma^2}(Y - X\hat{\beta})'(Y - X\hat{\beta}) \sim \chi^2 \]

with degrees of freedom equal to

\[ \text{trace } [I - X(X'X)^{-1}X'] \]

and non-centrality parameter

\[ \left( \frac{X\beta}{\sigma} \right)' [I - X(X'X)^{-1}X'] \left( \frac{X\beta}{\sigma} \right). \]

One can verify that

\[ \text{trace } [I - X(X'X)^{-1}X'] = n - p \]

and

\[ \left( \frac{X\beta}{\sigma} \right)' [I - X(X'X)^{-1}X'] \left( \frac{X\beta}{\sigma} \right) = 0. \]

Thus,

\[ \frac{1}{\sigma^2}(Y - X\hat{\beta})'(Y - X\hat{\beta}) \sim \chi^2_{(n-p)}. \]

Therefore, the error mean square \( S^2 = \frac{(Y - X\hat{\beta})'(Y - X\hat{\beta})}{(n-p)} \) is distributed as

\[ \frac{(n - p)S^2}{\sigma^2} \sim \chi^2_{(n-p)} \]

and the maximum likelihood estimator \( S^2_Y = \frac{(Y - X\hat{\beta})'(Y - X\hat{\beta})}{(n)} \) is distributed as

\[ \frac{nS^2_Y}{\sigma^2} \sim \chi^2_{(n-p)}. \]
A.2 Ordinary least squares estimators $\hat{\beta}$ is independent of error mean square

Consider the regression model defined in appendix A.1

$$Y = X\beta + \varepsilon.$$ 

The ordinary least squares estimator for $\beta$ is

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

where $b = (b_1, b_2, \ldots, b_p)'$, 

and given the normality assumption on $\varepsilon \sim N_n(0, \sigma^2 I_n)$,

$$b \sim N_p(\beta, \sigma^2(X'X)^{-1}).$$

An unbiased estimator of $\sigma^2$ is $S^2 = \frac{(Y - \hat{Y})'(Y - \hat{Y})}{(n-p)} = \frac{(Y - X\hat{\beta})'(Y - X\hat{\beta})}{(n-p)}$. We are to show that $b = \hat{\beta}$ and $S^2$ are independent.

For $\sigma$ fixed, $\hat{\beta}$ is a complete sufficient statistic for $\beta$ while $(Y - X\hat{\beta})'(Y - X\hat{\beta})$ is an ancillary statistic for $\beta$.

Recall Basu’s theorem (Basu; 1955, Lehmann; 1981) that states any complete sufficient statistic is independent of any ancillary statistic. Therefore, by Basu’s theorem, we conclude that $\hat{\beta}$ and $(Y - X\hat{\beta})'(Y - X\hat{\beta})$ are independent. Since $S^2$ is a function of $(Y - X\hat{\beta})'(Y - X\hat{\beta})$, we have $\hat{\beta}$ and $S^2$ are independent.

A.3 U and V are independent

Consider the regression model defined in appendix A.1

$$Y = X\beta + \varepsilon.$$ 

The ordinary least squares estimator for $\beta$ is

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

where $b = (b_1, b_2, \ldots, b_p)'$, 

and given the normality assumption on $\varepsilon \sim N_n(0, \sigma^2 I_n)$,

$$b \sim N_p(\beta, \sigma^2(X'X)^{-1}).$$
and

$$Y \sim N_n(X\beta, \sigma^2 I_n).$$

An unbiased estimator of $\sigma^2$ is

$$S^2 = (Y - \hat{Y})'(Y - \hat{Y})/(n - p) = \frac{\Sigma(Y_j - \hat{Y}_j)^2}{n - p} = \text{Error MS, } j = 1, 2, \ldots, n.$$

Now, the total variability in the data $(Y - X\beta)'(Y - X\beta)$ can be decomposed into two parts as

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

$$= \left[(Y - \hat{Y}) + X(b - \beta)\right]'\left[(Y - \hat{Y}) + X(b - \beta)\right]$$

$$= (Y - \hat{Y})'(Y - \hat{Y}) + (Y - \hat{Y})'X(b - \beta)$$

$$+ (\hat{b} - \beta)'X'(Y - \hat{Y}) + (\hat{b} - \beta)'XX(b - \beta)$$

$$= (Y - \hat{Y})'(Y - \hat{Y}) + (Y'X - \hat{Y}'X)(b - \beta)$$

$$+ (\hat{b} - \beta)(X'Y - X'\hat{Y}) + (\hat{b} - \beta)'X'X(b - \beta).$$

If we put $\hat{Y}'X = Y'X$ and $X'\hat{Y} = X'Y$ in the above equation we get

$$(Y - X\beta)'(Y - X\beta) = (Y - \hat{Y})'(Y - \hat{Y}) + (\hat{b} - \beta)'X'X(b - \beta).$$

It implies

$$\frac{1}{\sigma^2}(Y - X\beta)'(Y - X\beta) = \frac{1}{\sigma^2}(Y - \hat{Y})'(Y - \hat{Y}) + \frac{1}{\sigma^2}(\hat{b} - \beta)'X'X(b - \beta).$$

Now,

$$\frac{1}{\sigma^2}(Y - X\beta)'(Y - X\beta) = (Y - X\beta)'(\sigma^2 I_n)^{-1}(Y - X\beta) \sim \chi^2_n,$$

$$\frac{1}{\sigma^2}(Y - \hat{Y})'(Y - \hat{Y}) = \frac{\Sigma(Y_j - \hat{Y}_j)^2}{\sigma^2} \sim \chi^2_{n-p}$$

and

$$\frac{1}{\sigma^2}(\hat{b} - \beta)'X'X(b - \beta) = (\hat{b} - \beta)'(\sigma^2 (X'X)^{-1})^{-1}(b - \beta) \sim \chi^2_p.$$

Recall **Cochran’s theorem** (Montgomery; 2006):

Let $Z_i$ be NID(0,1) for $i = 1, 2, \ldots, v$ and

$$\sum Z_i^2 = Q_1 + Q_2 + \ldots + Q_s,$$

where $s \leq v$ and $Q_j$ has $v_j$ degrees of freedom ($j = 1, 2, \ldots, s$). Then $Q_1, Q_2, \ldots, Q_s$ are independent chi-square random variables with $v_1, v_2, \ldots, v_s$ degrees of freedom, respectively, if and only if

$$v = v_1 + v_2 + \ldots + v_s.$$

Because the degrees of freedom of $\frac{1}{\sigma^2}(Y - \hat{Y})'(Y - \hat{Y})$ and $\frac{1}{\sigma^2}(b - \beta)'X'X(b - \beta)$ add to $n$, the total degrees of freedom, Cochran’s theorem implies that they are independently distributed chi-square random variables.

Now, $V = \frac{S^2}{\sigma^2 x^2} = \frac{(Y - \hat{Y})'(Y - \hat{Y})}{(n - p)\sigma^2 x^2}$ is a function of $\frac{1}{\sigma^2}(Y - \hat{Y})'(Y - \hat{Y})$. Therefor, $V$ and $U = \frac{1}{\sigma^2}(b - \beta)'X'X(b - \beta)$ are independent of each other.
Bibliography


Vita Auctoris

Quazi Imad Uddin Ibrahim was born in 1976 in Sylhet, a district town in Bangladesh. He completed his Higher Secondary School studies in 1993 from M.C. College. From there he went on to the University of Dhaka where he obtained a B.Sc. in Statistics in 1998 and M.Sc. in 2000. He is currently a candidate for the Master degree in Statistics at the University of Windsor and hopes to graduate in June 2009.