

Collection of Biostatistics Research Archive
COBRA Preprint Series

Year 2007

Paper 26

The Existence of Maximum Likelihood
Estimates for the Binary Response Logistic
Regression Model

William F. McCarthy*

*Maryland Medical Research Institute, dr.w.f.mccarthy@gmail.com

This working paper is hosted by The Berkeley Electronic Press (bepress) and may not be commercially reproduced without the permission of the copyright holder.

<http://biostats.bepress.com/cobra/art26>

Copyright ©2007 by the author.

The Existence of Maximum Likelihood Estimates for the Binary Response Logistic Regression Model

William F. McCarthy

Abstract

The existence of maximum likelihood estimates for the binary response logistic regression model depends on the configuration of the data points in your data set. There are three mutually exclusive and exhaustive categories for the configuration of data points in a data set: Complete Separation, Quasi-Complete Separation, and Overlap. For this paper, a binary response logistic regression model is considered. A 2 x 2 tabular presentation of the data set to be modeled is provided for each of the three categories mentioned above. In addition, the paper will present an example of a data set whose data points have a linear dependency. Both unconditional maximum likelihood estimation (asymptotic inference) and exact conditional estimation (exact inference) will be considered and contrasted in terms of results. The statistical software package SAS will be used for the binary response logistic regression modeling.

Introduction

The Existence of Maximum Likelihood Estimates for the Logistic Regression Model depends on the configuration of the data points in your data set (Albert and Anderson, 1984; Santner and Duffy, 1985; So, 1995). There are three mutually exclusive and exhaustive categories for the configuration of data points in a data set:

- Complete Separation
- Quasi-Complete Separation
- Overlap

Refer to So (1995) for a nice graphical illustration of these three categories. For this paper, a binary response logistic regression model is considered. A 2 x 2 tabular presentation of the data set to be modeled is provided for each of the three categories mentioned above. In addition, the paper will present an example of a data set whose data points have a linear dependency.

Unconditional maximum likelihood estimation (asymptotic inference) is used when matched data are not considered, provided that the total number of variables in the model is not too large relative to the number of observations (Kleinbaum, 1994). This method of inference is based on maximizing the likelihood function for parameter estimation using the unconditional formula (Kleinbaum, 1994). This is the usual large-sample asymptotic method used by most of the current statistical software packages (Kleinbaum, 1994; Mehta and Patel, 1995).

The existence and uniqueness of maximum likelihood parameter estimates for the logistic regression model depends on the pattern of the data points in the observation space (Albert and Anderson, 1984; Santer and Duffy, 1986; So, 1993).

Complete Separation of data points gives non-unique infinite parameter estimates. Thus, maximum likelihood parameter estimates do not exist. Quasi-Complete Separation of data points also gives non-unique infinite parameter estimates. Thus, maximum likelihood parameter estimates do not exist. Maximum likelihood parameter estimates exist and are unique when there is an Overlap of data points. Complete separation and quasi-complete separation of data points usually occur with small data sets. Complete separation can occur for any type of data, but quasi-complete separation is not likely for quantitative data.

To contrast unconditional maximum likelihood estimation, exact conditional estimation will be considered as well. The theory of exact conditional logistic regression analysis (exact inference) was first proposed by Cox (1970). The computational methods employed in the statistical software package SAS (PROC LOGISTIC) are described in Hirji, Mehta, and Patel (1987), Hirji (1992), and Mehta, Patel, and Senchaudhuri (1992).

Exact conditional inference is based on generating the conditional distribution for the sufficient statistics of the parameters of interest. This distribution is called the permutation or exact conditional distribution. If the sufficient statistic of the β being estimated lies at one extreme of its range, a median unbiased estimate is reported (Hirji, Tsiatis, and Mehta 1989).

Methods

This paper will use both asymptotic and exact inference when modeling the data and will present the SAS output obtained when each of the four data sets are used for modeling. The emphasis of this paper is to show how SAS handles these four data sets when both asymptotic and exact inference is used with respect to a binary response logistic regression modeling. The outcome variable is binary (Mutation; YES, NO) and the covariate is categorical (Drug; EXPOSURE, NON-EXPOSURE). An intercept (Constant) term will be included in the model as well.

Data Sets that will be considered in this paper:

Complete Separation

	Mutation=NO	Mutation=YES	Total
Drug=NON-EXPOSURE	0	14	14
Drug=EXPOSURE	37	0	37
Total	37	14	51

Quasi-Complete Separation

	Mutation=NO	Mutation=YES	Total
Drug=NON-EXPOSURE	12	0	12
Drug=EXPOSURE	25	14	39
Total	37	14	51

Overlap

	Mutation=NO	Mutation=YES	Total
Drug=NON-EXPOSURE	9	3	12
Drug=EXPOSURE	25	14	39
Total	34	17	51

Linear Dependency

	Mutation=NO	Mutation=YES	Total
Drug=NON-EXPOSURE	0	0	0
Drug=EXPOSURE	37	14	51
Total	37	14	51



SAS Output

The SAS output for asymptotic and exact inference when considering the Complete Separation data set is presented below.

Complete Separation

	Mutation=NO	Mutation=YES	Total
Drug=NON-EXPOSURE	0	14	14
Drug=EXPOSURE	37	0	37
Total	37	14	51

The LOGISTIC Procedure

Model Information

Data Set	WORK.TEST
Response Variable	mutation
Number of Response Levels	2
Number of Observations	51
Model	binary logit
Optimization Technique	Fisher's scoring

Response Profile

Ordered Value	mutation	Total Frequency
1	1	14
2	0	37

Probability modeled is mutation=1.

Model Convergence Status

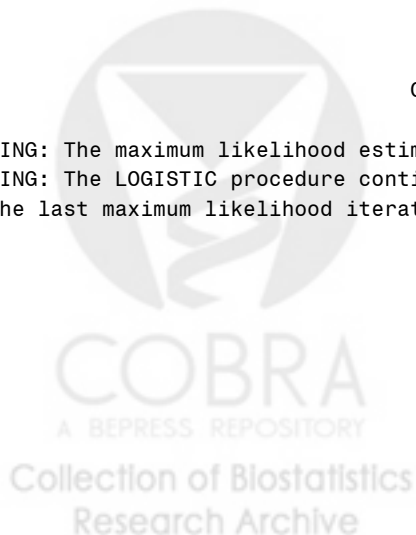
Complete separation of data points detected.

WARNING: The maximum likelihood estimate does not exist.

WARNING: The LOGISTIC procedure continues in spite of the above warning. Results shown are based on the last maximum likelihood iteration. Validity of the model fit is questionable.

Model Fit Statistics

Criterion	Intercept Only	Intercept and Covariates
AIC	61.945	4.007
SC	63.877	7.871
-2 Log L	59.945	0.007



Testing Global Null Hypothesis: BETA=0

Test	Chi-Square	DF	Pr > ChiSq
Likelihood Ratio	59.9375	1	<.0001
Score	51.0000	1	<.0001
Wald	0.2295	1	0.6319

Analysis of Maximum Likelihood Estimates

Parameter	DF	Estimate	Standard Error	Wald Chi-Square	Pr > ChiSq
Intercept	1	9.7773	35.4872	0.0759	0.7829
drug	1	-19.2725	40.2338	0.2295	0.6319

The LOGISTIC Procedure

WARNING: The validity of the model fit is questionable.

Odds Ratio Estimates

Effect	Point Estimate	95% Wald Confidence Limits
drug	<0.001	<0.001 >999.999

Association of Predicted Probabilities and Observed Responses

Percent Concordant	100.0	Somers' D	1.000
Percent Discordant	0.0	Gamma	1.000
Percent Tied	0.0	Tau-a	0.406
Pairs	518	c	1.000

Wald Confidence Interval for Parameters

Parameter	Estimate	95% Confidence Limits
Intercept	9.7773	-59.7764 79.3309
drug	-19.2725	-98.1293 59.5842



The LOGISTIC Procedure

Exact Conditional Analysis

Conditional Exact Tests

Effect	Test	Statistic	--- p-Value ---	
			Exact	Mid
Intercept	Score	14.0000	0.0001	<.0001
	Probability	0.000061	0.0001	<.0001
drug	Score	50.0000	<.0001	<.0001
	Probability	7.74E-13	<.0001	<.0001

Exact Parameter Estimates

Parameter	Estimate	95% Confidence Limits		p-Value
Intercept	2.9807*	1.1991	Infinity	0.0001
drug	-6.4343*	-Infinity	-4.1539	<.0001

NOTE: * indicates a median unbiased estimate.

The SAS output for asymptotic and exact inference when considering the Quasi-Complete Separation data set is presented below.

Quasi-Complete Separation

	Mutation=NO	Mutation=YES	Total
Drug=NON-EXPOSURE	12	0	12
Drug=EXPOSURE	25	14	39
Total	37	14	51

The LOGISTIC Procedure

Model Information

Data Set	WORK.TEST
Response Variable	mutation
Number of Response Levels	2
Number of Observations	51
Model	binary logit
Optimization Technique	Fisher's scoring



Response Profile

Ordered Value	mutation	Total Frequency
1	1	14
2	0	37

Probability modeled is mutation=1.

Model Convergence Status

Quasi-complete separation of data points detected.

WARNING: The maximum likelihood estimate may not exist.

WARNING: The LOGISTIC procedure continues in spite of the above warning. Results shown are based on the last maximum likelihood iteration. Validity of the model fit is questionable.

Model Fit Statistics

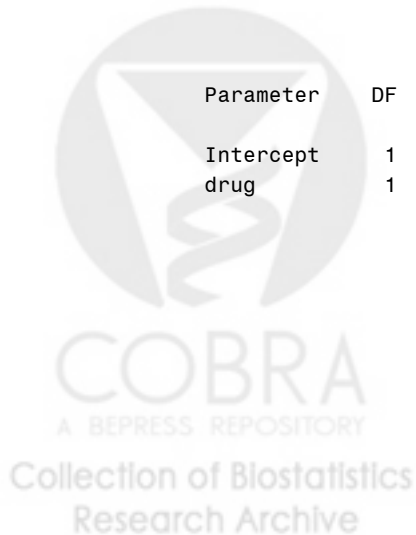
Criterion	Intercept Only	Intercept and Covariates
AIC	61.945	54.920
SC	63.877	58.784
-2 Log L	59.945	50.920

Testing Global Null Hypothesis: BETA=0

Test	Chi-Square	DF	Pr > ChiSq
Likelihood Ratio	9.0242	1	0.0027
Score	5.9376	1	0.0148
Wald	0.0028	1	0.9581

Analysis of Maximum Likelihood Estimates

Parameter	DF	Estimate	Standard Error	Wald Chi-Square	Pr > ChiSq
Intercept	1	-13.4954	246.0	0.0030	0.9562
drug	1	12.9155	246.0	0.0028	0.9581



The LOGISTIC Procedure

WARNING: The validity of the model fit is questionable.

Odds Ratio Estimates

Effect	Point Estimate	95% Wald Confidence Limits	
drug	>999.999	<0.001	>999.999

Association of Predicted Probabilities and Observed Responses

Percent Concordant	32.4	Somers' D	0.324
Percent Discordant	0.0	Gamma	1.000
Percent Tied	67.6	Tau-a	0.132
Pairs	518	c	0.662

Wald Confidence Interval for Parameters

Parameter	Estimate	95% Confidence Limits	
Intercept	-13.4954	-495.6	468.6
drug	12.9155	-469.2	495.0

The LOGISTIC Procedure

Exact Conditional Analysis

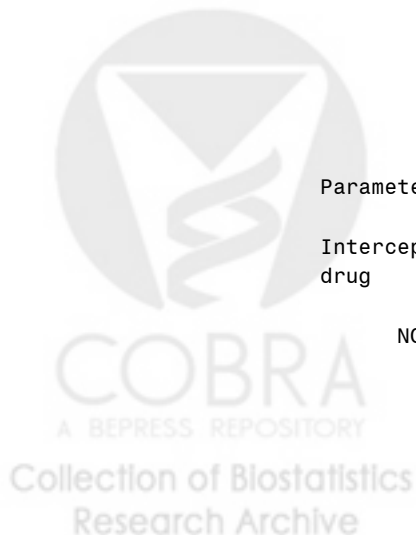
Conditional Exact Tests

Effect	Test	Statistic	--- p-Value ---	
			Exact	Mid
Intercept	Score	12.0000	0.0005	0.0004
	Probability	0.000244	0.0005	0.0004
drug	Score	5.8212	0.0224	0.0166
	Probability	0.0117	0.0224	0.0166

Exact Parameter Estimates

Parameter	Estimate	95% Confidence Limits		p-Value
Intercept	-2.8224*	-Infinity	-1.0219	0.0005
drug	2.1708*	0.2484	Infinity	0.0233

NOTE: * indicates a median unbiased estimate.



The SAS output for asymptotic and exact inference when considering the Overlap data set is presented below.

Overlap

	Mutation=NO	Mutation=YES	Total
Drug=NON-EXPOSURE	9	3	12
Drug=EXPOSURE	25	14	39
Total	34	17	51

The LOGISTIC Procedure

Model Information

Data Set WORK.TEST
 Response Variable mutation
 Number of Response Levels 2
 Number of Observations 51
 Model binary logit
 Optimization Technique Fisher's scoring

Response Profile

Ordered Value	mutation	Total Frequency
1	1	17
2	0	34

Probability modeled is mutation=1.

Model Convergence Status

Convergence criterion (GCONV=1E-8) satisfied.

Model Fit Statistics

Criterion	Intercept Only	Intercept and Covariates
AIC	66.924	68.416
SC	68.856	72.280
-2 Log L	64.924	64.416



Testing Global Null Hypothesis: BETA=0

Test	Chi-Square	DF	Pr > ChiSq
Likelihood Ratio	0.5080	1	0.4760
Score	0.4904	1	0.4838
Wald	0.4838	1	0.4867

Analysis of Maximum Likelihood Estimates

Parameter	DF	Estimate	Standard Error	Wald Chi-Square	Pr > ChiSq
Intercept	1	-1.0984	0.6666	2.7148	0.0994
drug	1	0.5186	0.7455	0.4838	0.4867

Odds Ratio Estimates

Effect	Point Estimate	95% Wald Confidence Limits
drug	1.680	0.390 7.241

The LOGISTIC Procedure

Association of Predicted Probabilities and Observed Responses

Percent Concordant	21.8	Somers' D	0.088
Percent Discordant	13.0	Gamma	0.254
Percent Tied	65.2	Tau-a	0.040
Pairs	578	c	0.544

Wald Confidence Interval for Parameters

Parameter	Estimate	95% Confidence Limits
Intercept	-1.0984	-2.4050 0.2082
drug	0.5186	-0.9427 1.9798

The LOGISTIC Procedure

Exact Conditional Analysis

Conditional Exact Tests



Effect	Test	Statistic	--- p-Value ---	
			Exact	Mid
Intercept	Score	3.0000	0.1460	0.1191
	Probability	0.0537	0.1460	0.1191
drug	Score	0.4808	0.7278	0.6155
	Probability	0.2247	0.7278	0.6155

Exact Parameter Estimates

Parameter	Estimate	95% Confidence Limits		p-Value
Intercept	-1.0986	-2.8465	0.2894	0.1460
drug	0.5091	-1.0858	2.4087	0.7422

The SAS output for asymptotic and exact inference when considering the Linear Dependency data set is presented below.

Linear Dependency

	Mutation=NO	Mutation=YES	Total
Drug=NON-EXPOSURE	0	0	0
Drug=EXPOSURE	37	14	51
Total	37	14	51

The LOGISTIC Procedure

Model Information

Data Set	WORK.TEST
Response Variable	mutation
Number of Response Levels	2
Number of Observations	51
Model	binary logit
Optimization Technique	Fisher's scoring

Response Profile

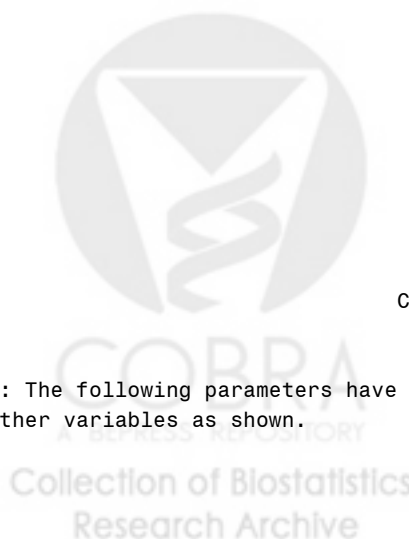
Ordered Value	mutation	Total Frequency
1	1	14
2	0	37

Probability modeled is mutation=1.

Model Convergence Status

Convergence criterion (GCONV=1E-8) satisfied.

NOTE: The following parameters have been set to 0, since the variables are a linear combination of other variables as shown.



drug = Intercept

Analysis of Maximum Likelihood Estimates

Parameter	DF	Estimate	Standard Error	Wald Chi-Square	Pr > ChiSq
Intercept	1	-0.9719	0.3138	9.5933	0.0020
drug	0	0	.	.	.

Wald Confidence Interval for Parameters

Parameter	Estimate	95% Confidence Limits	
Intercept	-0.9719	-1.5869	-0.3569

There was no SAS Output for Exact Conditional Analysis.

Results

Complete Separation Data Set:

- Unconditional maximum likelihood estimation (asymptotic inference)

The SAS output provided the following information:

Model Convergence Status

Complete separation of data points detected.

WARNING: The maximum likelihood estimate does not exist.

WARNING: The LOGISTIC procedure continues in spite of the above warning. Results shown are based on the last maximum likelihood iteration. Validity of the model fit is questionable.

The standard errors of the point estimates for the intercept ($se = 35.4872$) and drug ($se = 40.2338$) were large compared to the point estimates for the intercept ($\beta = 9.7773$) and drug ($\beta = -19.2725$). This is typically seen when the maximum likelihood parameter estimates do not converge during the modeling procedure. In addition, one sees that the p-values were both non-significant ($p > 0.05$) for the intercept ($p = 0.7829$) and drug ($p = 0.6319$).

- Exact conditional estimation (exact inference)

The SAS output provided the following information:

A median unbiased estimate of the intercept (MU $\beta = 2.9807$, 95% exact CI [1.1991, ∞]) and drug (MU $\beta = -6.4343$, 95% exact CI [$-\infty$, -4.1539]) are provided. One also sees that the exact p-values were both significant (intercept, $p = 0.0001$; drug, $p < 0.0001$).

Quasi-Complete Separation Data Set:

- Unconditional maximum likelihood estimation (asymptotic inference)

The SAS output provided the following information:

Model Convergence Status

Quasi-complete separation of data points detected.

WARNING: The maximum likelihood estimate may not exist.

WARNING: The LOGISTIC procedure continues in spite of the above warning. Results shown are based on the last maximum likelihood iteration. Validity of the model fit is questionable.

The standard errors of the point estimates for the intercept (se= 246.0) and drug (se= 246.0) were very large compared to the point estimates for the intercept ($\beta = -13.4954$) and drug ($\beta = 12.9155$). This is typically seen when the maximum likelihood parameter estimates do not converge during the modeling procedure. In addition, one sees that the p-values were both non-significant ($p > 0.05$) for the intercept ($p = 0.9562$) and drug ($p = 0.9581$).

- Exact conditional estimation (exact inference)

The SAS output provided the following information:

A median unbiased estimate of the intercept (MU $\beta = -2.8224$, 95% exact CI $[-\infty, -1.0219]$) and drug (MU $\beta = 2.1708$, 95% exact CI $[0.2484, \infty]$) are provided. One also sees that the exact p-values were both significant (intercept, $p = 0.0005$; drug, $p < 0.0233$).

Overlap Data Set:

- Unconditional maximum likelihood estimation (asymptotic inference)

The SAS output provided the following information:

Model Convergence Status

Convergence criterion (GCONV=1E-8) satisfied.

The standard errors of the point estimates for the intercept (se= 0.6666) and drug (se= 0.7455) were of reasonable size compared to the point estimates for the intercept ($\beta = -1.0984$) and drug ($\beta = 0.5186$). This is typically seen when the maximum likelihood parameter estimates does converge during the modeling procedure. In addition, one sees that the p-values were both non-significant ($p > 0.05$) for the intercept ($p = 0.0994$) and drug ($p = 0.4867$).

- Exact conditional estimation (exact inference)

The SAS output provided the following information:

An exact estimate of the intercept ($\beta = -1.0986$, 95% exact CI $[-2.8465, 0.2894]$) and drug ($\beta = 0.5091$, 95% exact CI $[-1.0858, 2.4087]$) are provided. One also sees that the exact p-values were both non-significant (intercept, $p = 0.1460$; drug, $p = 0.7422$).

Linear Dependency Data Set:

- Unconditional maximum likelihood estimation (asymptotic inference)

The SAS output provided the following information:

Model Convergence Status

Convergence criterion (GCONV=1E-8) satisfied.

NOTE: The following parameters have been set to 0, since the variables are a linear combination of other variables as shown.

```
drug = Intercept
```

The standard error of the point estimate for the intercept (se= 0.3138) was of reasonable size compared to the point estimates for the intercept ($\beta = -0.9719$). This is typically seen when the maximum likelihood parameter estimates does converge during the modeling procedure. The point estimate and the standard error of the point estimate for drug were not computed because of the linear dependency between the two parameters. The p-value for the intercept was significant ($p=0.0020$).

- Exact conditional estimation (exact inference)

Because of the linear dependency, no SAS output was generated for the exact conditional analysis.

Take Home Points

- The Maximum Likelihood Estimates **do not exist** when you have a data set with **complete separation**.
- The Maximum Likelihood Estimates **may not exist** when you have a data set with **quasi-complete separation**.
- The Maximum Likelihood Estimates **do exist** when you have a data set with **overlap**.
- The Maximum Likelihood Estimates **do exist** when you have a data set with **linear dependency**.
- Exact Conditional Logistic Regression Analysis **can be more informative** than Unconditional Maximum Likelihood Logistic Regression Analysis.

References

1. Albert A. and Anderson JA (1984). On the Existence of Maximum Likelihood Estimates in Logistic Regression Models. **Biometrika**, 71, pp 1-10.
2. Cox, D.R. (1970), **Analysis of Binary Data**, New York: Chapman and Hall.
3. Hirji, K.F., Mehta, C.R., and Patel, N.R. (1987), Computing Distributions for Exact Logistic Regression, **Journal of the American Statistical Association**, 82, pp 1110 - 1117.
4. Hirji, K.F., Tsiatis, A.A., and Mehta, C.R. (1989), Median Unbiased Estimation for Binary Data, **American Statistician**, 43, pp 7 - 11.
5. Hirji, K.F. (1992), Computing Exact Distributions for Polytomous Response Data, **Journal of the American Statistical Association**, 87, pp 487 - 492.
6. Kleinbaum, D.G. (1994). **Logistic Regression: A Self-learning Text**. Springer-Verlag, NY, NY. pp 104-119.
7. Mehta, C.R., Patel, N. and Senchaudhuri, P. (1992), Exact Stratified Linear Rank Tests for Ordered Categorical and Binary Data, **Journal of Computational and Graphical Statistics**, 1, pp 21 - 40.
8. Mehta, C.R. and Patel, N.R. (1995), Exact Logistic Regression: Theory and Examples, **Statistics in Medicine**, 14, pp 2143 - 2160.
9. Santner TJ and Duffy ED (1986). A note on A. Albert and J.A. Anderson's Conditions for the Existence of Maximum Likelihood Estimates in Logistic Regression Models. **Biometrika**, 73, pp 755-758.
10. So Y (1995). A Tutorial on Logistic Regression. **SUGI Proceedings**.
<http://support.sas.com/techsup/technote/ts450.pdf>

