Challenger Data Example

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Contents

Background Challenger Explosion

The Space Shuttle Challenger disaster was a fatal incident in the United States' space program that occurred on January 28, 1986, when the Space Shuttle Challenger (OV-099) broke apart 73 seconds into its flight, killing all seven crew members aboard. The crew consisted of five NASA astronauts, and two payload specialists. The mission carried the designation STS-51-L and was the tenth flight for the Challenger orbiter.

The spacecraft disintegrated over the Atlantic Ocean, off the coast of Cape Canaveral, Florida, at 11:39 a.m. EST (16:39 UTC). The disintegration of the vehicle began after a joint in its right solid rocket booster (SRB) failed at liftoff. The failure was caused by the failure of O-ring seals used in the joint that were not designed to handle the unusually cold conditions that existed at this launch. The seals' failure caused a breach in the SRB joint, allowing pressurized burning gas from within the solid rocket motor to reach the outside and impinge upon the adjacent SRB aft field joint attachment hardware and external fuel tank. This led to the separation of the right-hand SRB's aft field joint attachment and the structural failure of the external tank. Aerodynamic forces broke up the orbiter.

Left: STS-51L crew members Michael J. Smith, front row left, Francis R. "Dick" Scobee, Ronald E. McNair; Ellison S. Onizuka, back row left, S. Christa McAuliffe, Gregory B. Jarvis, and Judith A. Resnik. Right: The STS-51L crew patch, with the red apple symbolizing McAuliffe's Teacher in Space program.

The crew compartment and many other vehicle fragments were eventually recovered from the ocean floor after a lengthy search and recovery operation. The exact timing of the death of the crew is unknown; several crew members are known to have survived the initial breakup of the spacecraft. The shuttle had no escape system, and the impact of the crew compartment at terminal velocity with the ocean surface was too violent to be survivable.

The disaster resulted in a 32-month hiatus in the Space Shuttle program and the formation of the Rogers Commission, a special commission appointed by United States President Ronald Reagan to investigate the accident. The Rogers Commission found that NASA's organizational culture and decision-making processes had been key contributing factors to the accident, with the agency violating its own safety rules. NASA managers had known since 1977 that contractor Morton-Thiokol's design of the SRBs contained a potentially catastrophic flaw in the O-rings, but they had failed to address this problem properly. NASA managers also disregarded warnings from engineers about the dangers of launching posed by the low temperatures of that morning, and failed to adequately report these technical concerns to their superiors.

Approximately 17 percent of the US population witnessed the launch on live television broadcast because of the presence of high school teacher Christa McAuliffe, who would have been the first teacher in space. Media coverage of the accident was extensive; one study reported that 85 percent of Americans surveyed had heard the news within an hour of the accident. The Challenger disaster has been used as a case study in many discussions of engineering safety and workplace ethics.

O-Ring Concerns

Each of the two solid rocket boosters (SRBs) was constructed of seven sections, six of which were permanently joined in pairs at the factory. For each flight, the four resulting segments were then assembled in the Vehicle Assembly Building at Kennedy Space Center (KSC), with three field joints. The factory joints were sealed with asbestos-silica insulation applied over the joint, while each field joint was sealed with two rubber O-rings. After the destruction of Challenger, the number of O-rings per field joint was increased to three.[7] The seals of all of the SRB joints were required to contain the hot, high-pressure gases produced by the burning solid propellant inside, thus forcing them out of the nozzle at the aft end of each rocket.

During the Space Shuttle design process, a McDonnell Douglas report in September 1971 discussed the safety record of solid rockets. While a safe abort was possible after most types of failures, one was especially dangerous: a burnthrough by hot gases of the rocket's casing. The report stated that "if burnthrough occurs adjacent to [liquid hydrogen/oxygen] tank or orbiter, timely sensing may not be feasible and abort not possible", accurately foreshadowing the Challenger accident. Morton-Thiokol was the contractor responsible for the construction and maintenance of the shuttle's SRBs. As originally designed by Thiokol, the O-ring joints in the SRBs were supposed to close more tightly due to forces generated at ignition, but a 1977 test showed that when pressurized water was used to simulate the effects of booster combustion, the metal parts bent away from each other, opening a gap through which gases could leak. This phenomenon, known as "joint rotation", caused a momentary drop in air pressure. This made it possible for combustion gases to erode the O-rings. In the event of widespread erosion, a flame path could develop, causing the joint to burst—which would have destroyed the booster and the shuttle.

Engineers at the Marshall Space Flight Center wrote to the manager of the Solid Rocket Booster project, George Hardy, on several occasions suggesting that Thiokol's field joint design was unacceptable. For example, one engineer suggested that joint rotation would render the secondary O-ring useless, but Hardy did not forward these memos to Thiokol, and the field joints were accepted for flight in 1980.

Evidence of serious O-ring erosion was present as early as the second space shuttle mission, STS-2, which was flown by Columbia. Contrary to NASA regulations, the Marshall Center did not report this problem to senior management at NASA, but opted to keep the problem within their reporting channels with Thiokol. Even after the O-rings were redesignated as "Criticality 1"—meaning that their failure would result in the destruction of the Orbiter, no one at Marshall suggested that the shuttles be grounded until the flaw could be fixed.

After the 1984 launch of STS-41-D, flown by Discovery, the first occurrence of hot gas "blow-by" was discovered beyond the primary O-ring. In the post-flight analysis, Thiokol engineers found that the amount of blow-by was relatively small and had not impinged upon the secondary O-ring, and concluded that for future flights, the damage was an acceptable risk. However, after the Challenger disaster, Thiokol engineer Brian Russell identified this event as the first "big red flag" regarding O-ring safety.

By 1985, with seven of nine shuttle launches that year using boosters displaying O-ring erosion or hot gas blow-by, Marshall and Thiokol realized that they had a potentially catastrophic problem on their hands. Perhaps most concerning was the launch of STS-51-B in April 1985, flown by Challenger, in which the worst O-ring damage to date was discovered in post-flight analysis. The primary O-ring of the left nozzle had been eroded so extensively that it had failed to seal, and for the first time hot gases had eroded the secondary O-ring. They began the process of redesigning the joint with three inches (76 mm) of additional steel around the tang. This tang would grip the inner face of the joint and prevent it from rotating. They did not call for a halt to shuttle flights until the joints could be redesigned, but rather treated the problem as an acceptable flight risk. For example, Lawrence Mulloy, Marshall's manager for the SRB project since 1982, issued and waived launch constraints for six consecutive flights. Thiokol even went as far as to persuade NASA to declare the O-ring problem "closed".[General Donald Kutyna, a member of the Rogers Commission, later likened this situation to an airline permitting one of its planes to continue to fly despite evidence that one of its wings was about to fall off.

Theory

Logic Link Model

Let Y be a binary response variable where $\Pr[Y = 1 \mid \mathbf{x}] = \pi(\mathbf{x})$ and $\Pr[Y = 0 \mid \mathbf{x}] = 1 - \pi(\mathbf{x})$ with covariates $\mathbf{x} = (x_1, x_2, \ldots, x_p)$. There are several potential approaches to this modeling problem. One could use the ordinary least squares approach, called the **Linear Probability model**, given as,

$$\pi(\mathbf{x}) = \alpha + \beta'\mathbf{x}.$$

This model has a structural defect since $\pi(x)$ is not restricted to the interval $[0, 1]$ for all x. A better model is the **Logistic Regression Model** given as,

$$y = log\left[\frac{\pi(\mathbf{x})}{1 - \pi(\mathbf{x})}\right] = (\alpha + \beta'\mathbf{x}),$$

where y is the log odds and $\pi(\mathbf{x})$ is the probability of the event of interest for the covariate **x**. It follows that,

$$\frac{\pi(\mathbf{x})}{1 - \pi(\mathbf{x})} = exp(\alpha + \beta'\mathbf{x}),$$

and

$$\pi(\mathbf{x}) = \frac{exp(\alpha + \beta'\mathbf{x})}{1 + exp(\alpha + \beta'\mathbf{x})}.$$

Complementary Log-Log Model

The complementary log-log model provides an alternative model to the logit and probit that is asymmetric about 0.5 where

$$\pi(x) = 1 - \exp[-\exp(\alpha + \beta x)],$$

and

$$\log[-\log(1 - \pi(x))] = \alpha + \beta x.$$

Let x_1 and x_2 denote two values of the covariate, then

$$\log[-\log(1 - \pi(x_2))] - \log[-\log(1 - \pi(x_1))] = \beta(x_2 - x_1),$$

or

$$\frac{\log[1 - \pi(x_2)]}{\log[1 - \pi(x_1)]} = \exp[\beta(x_2 - x_1)].$$

In which case, one has

$$1 - \pi(x_2) = [1 - \pi(x_1)]^{\exp[\beta(x_2 - x_1)]}.$$

In this document I have provided the analysis for NASA Challenger data concerning the relationship that atmospheric temperature has with the performance and integrity of the O-rings. I will use the LOGIT and CLOGLOG link with the binary data.

R

Needed Packages

```
if(!require(FSA)){install.packages("FSA")}
if(!require(ggplot2)){install.packages("ggplot2")}
if(!require(car)){install.packages("car")}
if(!require(multcompView)){install.packages("multcompView")}
if(!require(lsmeans)){install.packages("lsmeans")}
if(!require(grid)){install.packages("grid")}
if(!require(nlme)){install.packages("nlme")}
if(!require(lme4)){install.packages("lme4")}
if(!require(Rmisc)){install.packages("Rmisc")}
#if(!require(rms)){install.packages("rms")}
#if(!require(FSA)){install.packages("FSA")}
#if(!require(lmerTest)){install.packages("lmerTest")}
#if(!require(rcompanion)){install.packages("rcompanion")}
```

Read data from SAS input file

```
Input = ("
temp td no_td
 53 1 0
 57 1 0
 58 1 0
 63 1 0
 66 0 1
 67 0 1
 67 0 1
 67 0 1
 68 0 1
 69 0 1
 70 1 0
 70 1 0
 70 0 1
 70 0 1
 72 0 1
 73 0 1
 75 1 0
 75 0 1
 76 0 1
 76 0 1
 78 0 1
 79 0 1
 81 0 1
")
Nasa = read.table(textConnection(Input),header=TRUE)
```

```r
Nasa = data.frame(Nasa)
# temp = "Atmospheric Temperature"
# td   = "failed attempts"
# no_td = "successful attempts"
# total = "number of attempts";
temp = Nasa$temp
td = Nasa$td
no.td = Nasa$no_td
total = td + no.td
per.fail = td/total
```

Descriptive Statistics

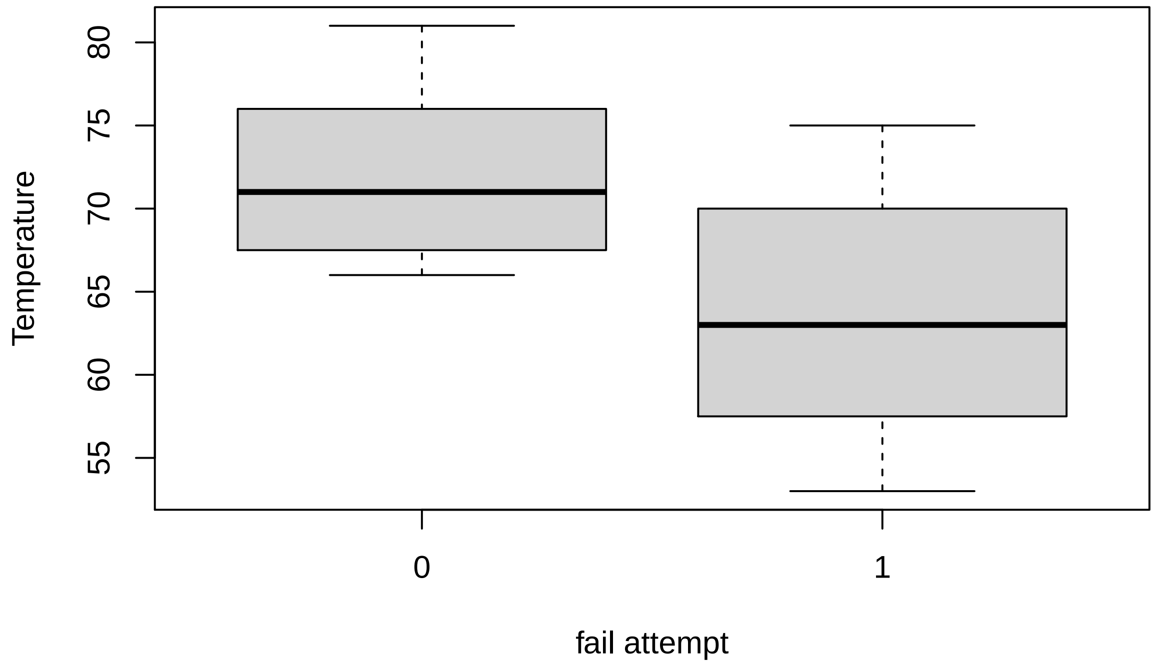
```r
library(Rmisc)

sum = summary(Nasa)
sum
```

```
##       temp             td               no_td
##  Min.   :53.00   Min.   :0.0000   Min.   :0.0000
##  1st Qu.:67.00   1st Qu.:0.0000   1st Qu.:0.0000
##  Median :70.00   Median :0.0000   Median :1.0000
##  Mean   :69.57   Mean   :0.3043   Mean   :0.6957
##  3rd Qu.:75.00   3rd Qu.:1.0000   3rd Qu.:1.0000
##  Max.   :81.00   Max.   :1.0000   Max.   :1.0000
```

Descriptive Plots where CA=1 is an O-ring failure

```r
boxplot(temp ~ td,
        data = Nasa,
        xlab = "fail attempt",
        ylab = "Temperature")
```



Fit Logistic Model with LOGIT link

```
mod1 = glm( td ~ temp,
            family = "binomial"(link="logit"),
            data=Nasa)
mod1
```

```
##
## Call:  glm(formula = td ~ temp, family = binomial(link = "logit"),
data = Nasa)
##
## Coefficients:
## (Intercept)         temp
##     15.0429      -0.2322
##
## Degrees of Freedom: 22 Total (i.e. Null);  21 Residual
## Null Deviance:       28.27
## Residual Deviance: 20.32     AIC: 24.32
```

```
#plot(mod1)
```

Fit Logistic Model with Cloglog link

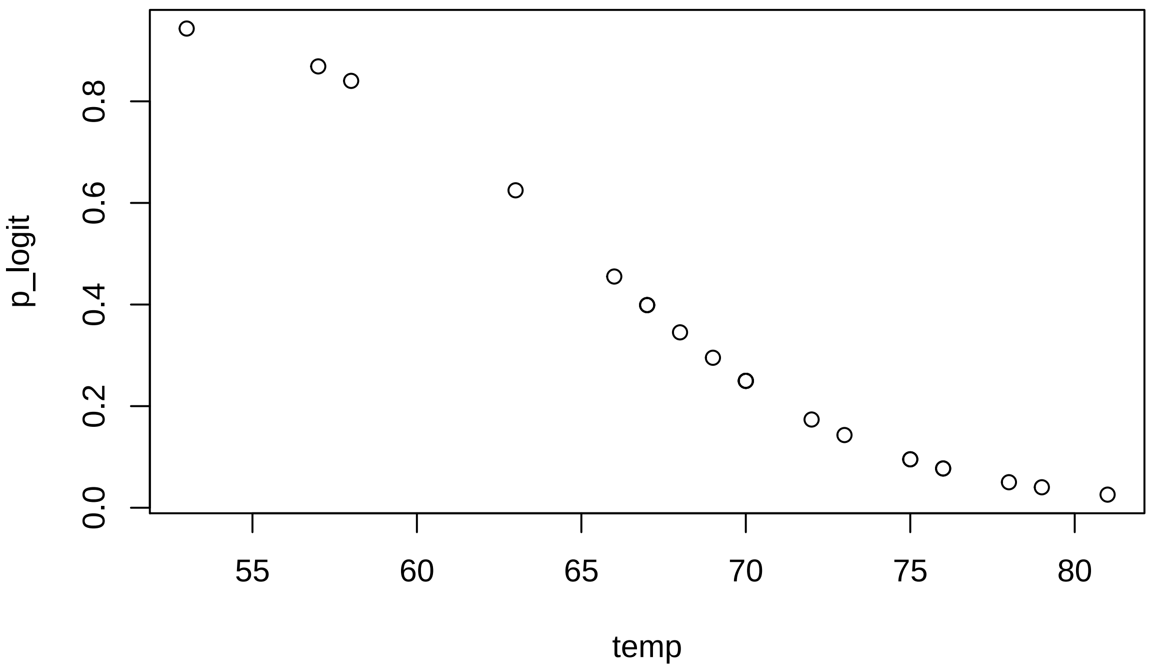
```
mod2 = glm( td ~ temp,
            family = "binomial"(link="cloglog"),
            data=Nasa)
mod2
```

```
##
## Call:  glm(formula = td ~ temp, family = binomial(link = "cloglog"),
##     data = Nasa)
##
## Coefficients:
## (Intercept)         temp
##     12.3022      -0.1958
##
## Degrees of Freedom: 22 Total (i.e. Null);  21 Residual
## Null Deviance:       28.27
## Residual Deviance: 19.53     AIC: 23.53
```

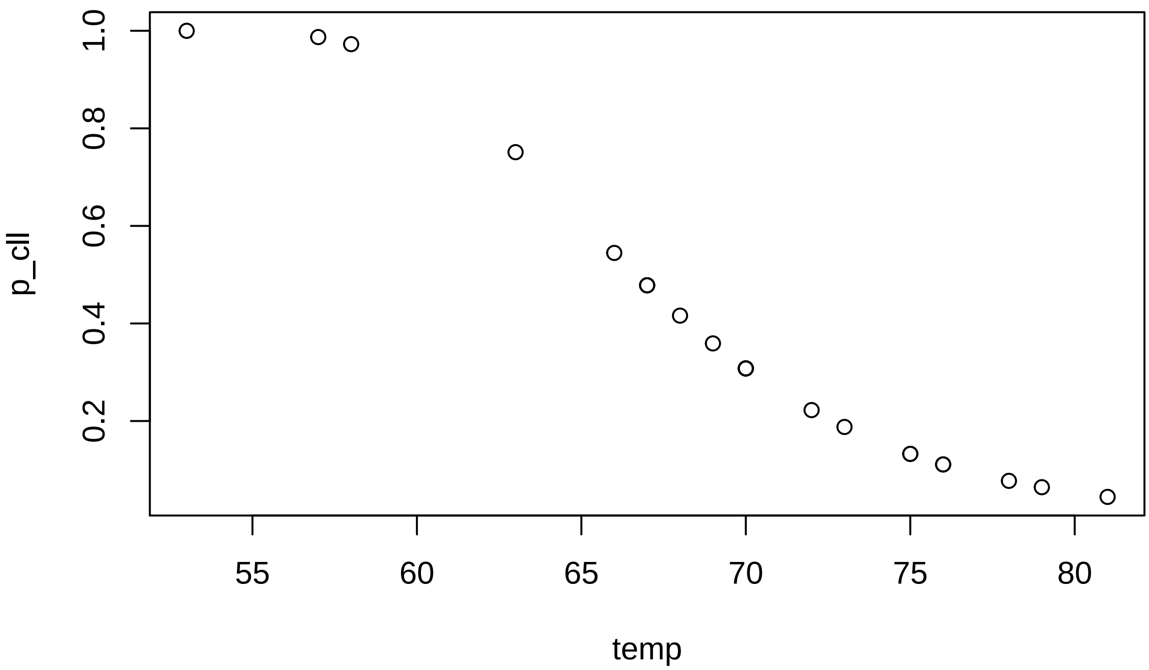
```
#plot(mod2)
```

Predicted Plots

```
#temperature = runif(100,45,85)
#temperature = order(temperature)
p_logit = exp(15.0 - 0.23*temp)/(1 + exp(15.0 - 0.23*temp))
p_cll = 1 - exp(-exp(12.3 - 0.19*temp))
plot(temp,p_logit)
```




```
plot(temp,p_cll)
```




```r
#diff=p_cll - p_logit
#plot(temperature,diff)
```

List of Predictive Probability of Failure

```r
cbind(temp, p_logit, p_cll)
```

```
##       temp    p_logit      p_cll
##  [1,]   53 0.94321382 0.99990856
##  [2,]   57 0.86875553 0.98708331
##  [3,]   58 0.84023800 0.97258431
##  [4,]   63 0.62480647 0.75116572
##  [5,]   66 0.45512111 0.54462219
##  [6,]   67 0.39891212 0.47821993
##  [7,]   67 0.39891212 0.47821993
##  [8,]   67 0.39891212 0.47821993
##  [9,]   68 0.34524654 0.41605264
## [10,]   69 0.29525430 0.35908476
## [11,]   70 0.24973989 0.30779937
## [12,]   70 0.24973989 0.30779937
## [13,]   70 0.24973989 0.30779937
## [14,]   70 0.24973989 0.30779937
## [15,]   72 0.17364665 0.22242763
## [16,]   73 0.14307272 0.18782966
## [17,]   75 0.09534946 0.13261650
## [18,]   75 0.09534946 0.13261650
```

```
## [19,]   76 0.07727220 0.11099715
## [20,]   76 0.07727220 0.11099715
## [21,]   78 0.05021127 0.07730783
## [22,]   79 0.04031042 0.06437152
## [23,]   81 0.02583124 0.04448226
```

SAS

Code

```
title "NASA Space Shuttle Failed Launches";
data Challenger;
  input temp td no_td;
  total=td+no_td;
  label temp = "Atmospheric Temperature"
        td = "failed attempts"
        no_td = "successful attempts"
        total = "number of attempts";
 datalines;
 53 1 0
 57 1 0
 58 1 0
 63 1 0
 66 0 1
 67 0 3
 68 0 1
 69 0 1
 70 2 2
 72 0 1
 73 0 1
 75 1 1
 76 0 2
 78 0 1
 79 0 1
 81 0 1
 ;
 title2 'Challenger Data';
title3 "Temperature Statistics at Launch";

proc means data=challenger;
     var temp;
run;

title3 'Observed Percent Failure by Temperature';

data a;set challenger;percent=td/total;

proc sgplot data=a; scatter x=temp y=percent;run;
```

```
title3 'Logistic Regression - LOGIT Link';
proc logistic data=challenger plots=effect;
  model td/total=temp/ link=logit expb;
run;

title3 'Logistic Regression - CLOGLOG Link';
proc logistic data=challenger plots=effect;
  model td/total=temp/ link=cloglog ;
run;
```

Output

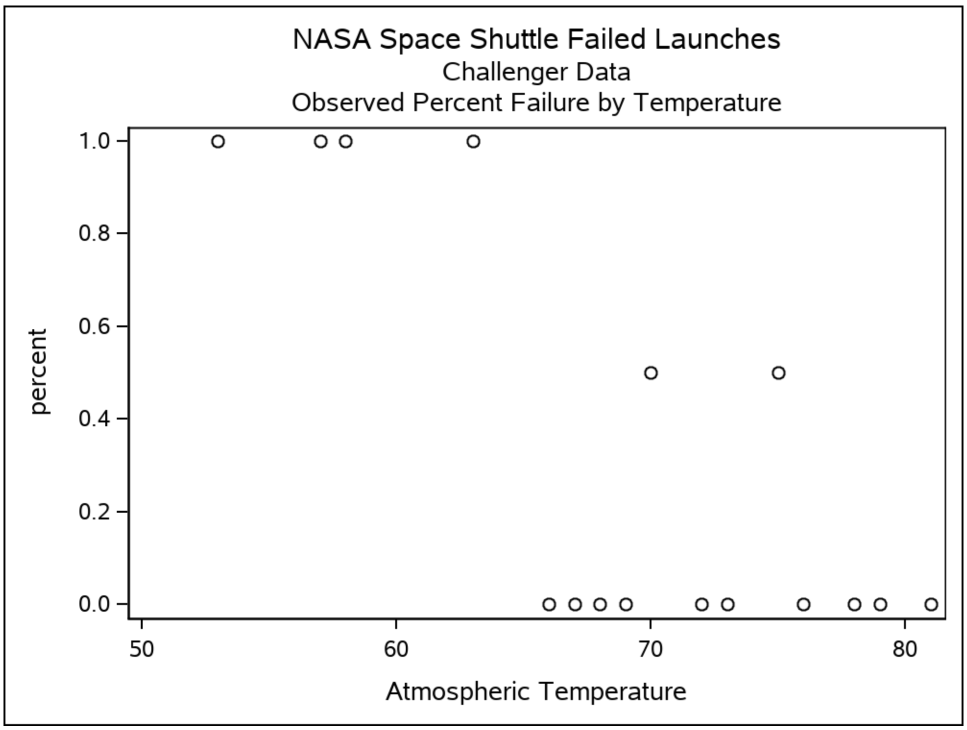
NASA Space Shuttle Failed Launches

Challenger Data

Temperature Statistics at Launch

The MEANS Procedure

Analysis Variable : temp Atmospheric Temperature				
N	**Mean**	**Std Dev**	**Minimum**	**Maximum**
16	69.0625000	8.1932391	53.0000000	81.0000000



NASA Space Shuttle Failed Launches

Challenger Data

Logistic Regression - LOGIT Link

The LOGISTIC Procedure

Model Information		
Data Set	WORK.CHALLENGER	
Response Variable (Events)	td	failed attempts
Response Variable (Trials)	total	number of attempts
Model	binary logit	
Optimization Technique	Fisher's scoring	

Number of Observations Read	16
Number of Observations Used	16
Sum of Frequencies Read	23
Sum of Frequencies Used	23

Response Profile		
Ordered Value	**Binary Outcome**	**Total Frequency**
1	Event	7
2	Nonevent	16

Model Convergence Status
Convergence criterion (GCONV=1E−8) satisfied.

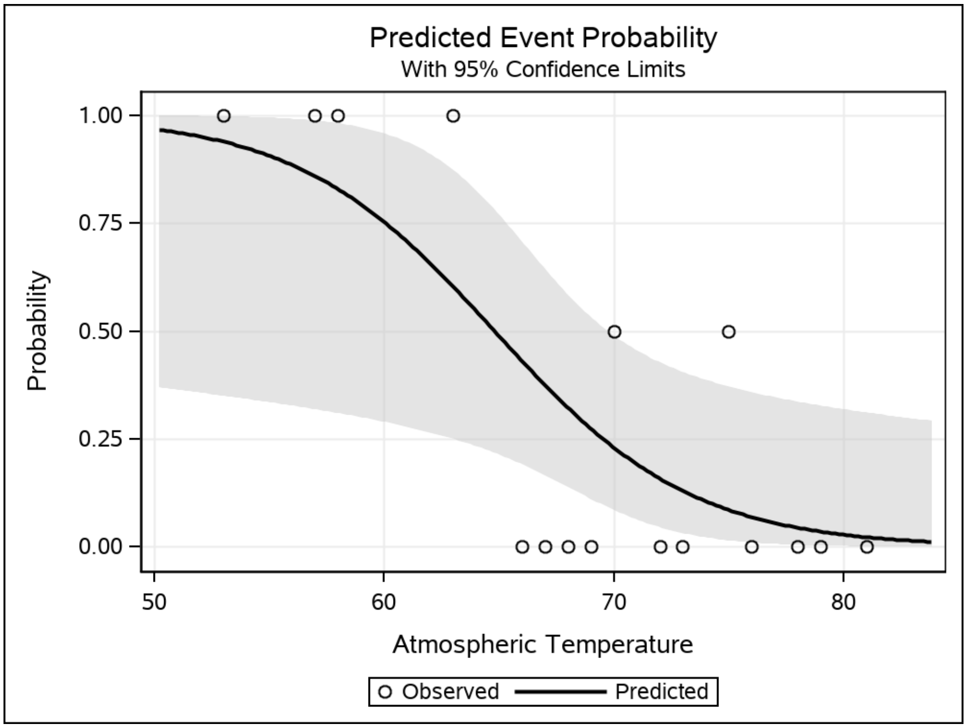
Model Fit Statistics			
Criterion	**Intercept Only**	**Intercept and Covariates**	
		Log Likelihood	**Full Log Likelihood**
AIC	30.267	24.315	19.345
SC	31.403	26.586	21.616
-2 Log L	28.267	20.315	15.345

Testing Global Null Hypothesis: BETA=0			
Test	**Chi-Square**	**DF**	**Pr > ChiSq**
Likelihood Ratio	7.9520	1	0.0048
Score	7.2312	1	0.0072
Wald	4.6008	1	0.0320

Analysis of Maximum Likelihood Estimates						
Parameter	**DF**	**Estimate**	**Standard Error**	**Wald Chi-Square**	**Pr > ChiSq**	**Exp(Est)**
Intercept	1	15.0429	7.3786	4.1563	0.0415	3412140
temp	1	−0.2322	0.1082	4.6008	0.0320	0.793

Odds Ratio Estimates			
Effect	**Point Estimate**	**95% Wald Confidence Limits**	
temp	0.793	0.641	0.980

Association of Predicted Probabilities and Observed Responses			
Percent Concordant	75.9	**Somers' D**	0.563
Percent Discordant	19.6	**Gamma**	0.589
Percent Tied	4.5	**Tau-a**	0.249
Pairs	112	**c**	0.781



Predicted Event Probability
With 95% Confidence Limits
Probability
1.00
0.75
0.50
0.25
0.00
50
60
70
80
Atmospheric Temperature
Observed
Predicted

NASA Space Shuttle Failed Launches
Challenger Data
Logistic Regression - CLOGLOG Link
The LOGISTIC Procedure

Model Information		
Data Set	WORK.CHALLENGER	
Response Variable (Events)	td	failed attempts
Response Variable (Trials)	total	number of attempts
Model	binary cloglog	
Optimization Technique	Fisher's scoring	

Number of Observations Read	16
Number of Observations Used	16
Sum of Frequencies Read	23
Sum of Frequencies Used	23

Response Profile		
Ordered Value	**Binary Outcome**	**Total Frequency**
1	Event	7
2	Nonevent	16

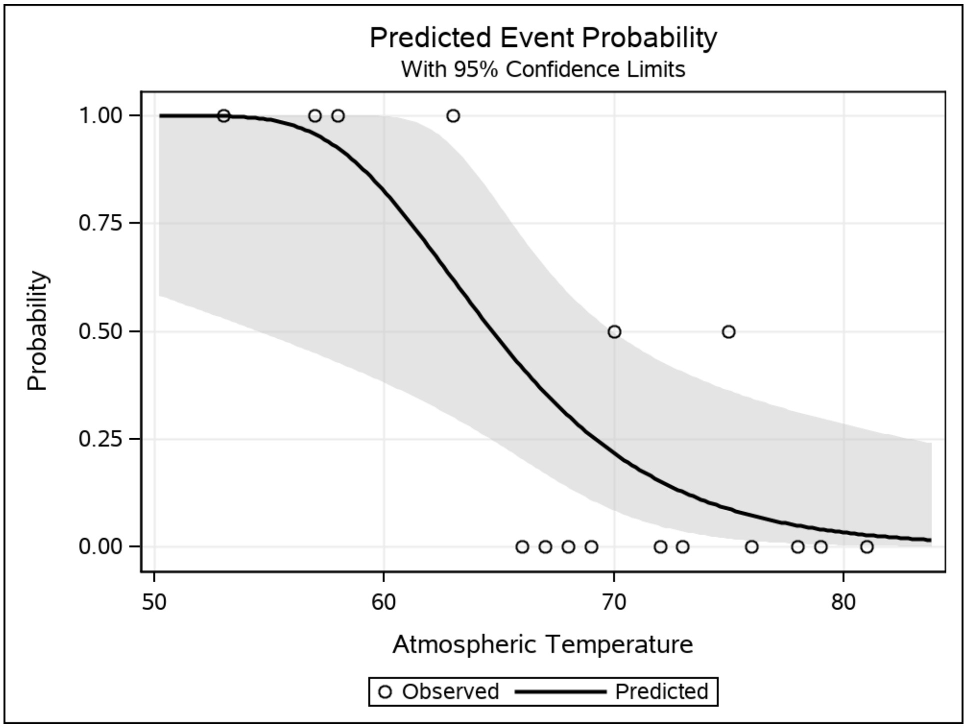
Model Convergence Status
Convergence criterion (GCONV=1E−8) satisfied.

Model Fit Statistics			
Criterion	**Intercept Only**	**Intercept and Covariates**	
		Log Likelihood	**Full Log Likelihood**
AIC	30.267	23.531	18.562
SC	31.403	25.802	20.833
-2 Log L	28.267	19.531	14.562

Testing Global Null Hypothesis: BETA=0			
Test	**Chi-Square**	**DF**	**Pr > ChiSq**
Likelihood Ratio	8.7357	1	0.0031
Score	7.2312	1	0.0072
Wald	6.2873	1	0.0122

Analysis of Maximum Likelihood Estimates					
Parameter	**DF**	**Estimate**	**Standard Error**	**Wald Chi-Square**	**Pr > ChiSq**
Intercept	1	12.3017	5.1953	5.6068	0.0179
temp	1	−0.1958	0.0781	6.2873	0.0122

Association of Predicted Probabilities and Observed Responses			
Percent Concordant	75.9	**Somers' D**	0.563
Percent Discordant	19.6	**Gamma**	0.589
Percent Tied	4.5	**Tau-a**	0.249
Pairs	112	**c**	0.781


Predicted Event Probability
With 95% Confidence Limits
Probability
1.00
0.75
0.50
0.25
0.00
50
60
70
80
Atmospheric Temperature
Observed
Predicted