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Stata tip 125: Binned residual plots for assessing the fit of regression models for binary outcomes

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Plots based on residuals, such as plots of residual-versus-fitted values, are now standard after fitting linear regression models. These plots are used to assess the validity of assumptions, to identify features not captured by the model, and to find problematic data points or clusters. However, such plots are typically not very useful for regression models for binary outcomes because of the discrete nature of residuals from these models. Binned residual plots, as recommended by Gelman and Hill (2007), can be used to assess both the overall fit of regression models for binary outcomes (for example, logistic or probit models) and the inclusion of continuous variables. I demonstrate the construction of such plots in Stata. These binned residual plots are related to those produced by the `rbinplot` command from the `modeldiag` package (Cox [2004], updated in Cox [2010]), with the addition of approximate confidence limits.

To construct a binned residual plot to assess the overall fit of a logistic regression model, one orders predicted probabilities from smallest to largest and calculates residuals. Data are split into bins containing equal numbers of observations (a recommended number of bins is the square root of the number of observations), and the average residual is plotted against the average predicted probability for each bin. For each bin, approximate 95% confidence limits are $\pm 2\sqrt{p(1-p)/n}$, estimated using the standard deviation of each bin's residuals.

If the model is correct, about 95% of the points are expected to lie within the confidence limits. As is the case for a residual-versus-fitted plot used for linear regression, departures from random scatter are indicative that the fitted model does not accurately describe the data. To assess the fit of a continuous covariate, one orders observations and constructs bins in terms of that covariate instead of in terms of the predicted probabilities. The average residual is then plotted against the average covariate in each bin.

To demonstrate the construction of these plots, I simulate an example dataset consisting of 5,000 observations, where the binary outcome (or response variable) is dependent on two continuous covariates and the square of one of these covariates:

```
. set obs 5000
obs was 0, now 5000
. set seed 86206
. generate x1 = rnormal()
. generate x2 = rnormal()
. generate prob_y = exp(-1+x1+x2+x1^2)/(1+exp(-1+x1+x2+x1^2))
. generate y = rbinomial(1, prob_y)
```

To demonstrate the usefulness of binned residual plots, I omit the squared term from the logistic regression model for the binary outcome.

```
. quietly logit y x1 x2
. predict pred_y, pr
. generate resid = y - pred_y
```

After I obtain the predicted probabilities for each observation, the construction of the binned residual plot proceeds as follows:

```
. sort pred_y
. generate myids = _n if pred_y < .
. local nbins = floor(sqrt(5000))
. egen binno = cut(myids) if pred_y < . , group(`nbins`) icodes
. egen avefit = mean(pred_y), by(binno)
. egen myaveres = mean(resid), by(binno)
. egen mysd = sd(resid), by(binno)
. egen mytag = tag(binno)
. bysort binno: egen binsize = count(pred_y)
. generate uplim = 2*mysd/sqrt(binsize)
. generate dwlim = -2*mysd/sqrt(binsize)
. graph twoway (scatter myaveres avefit if inrange(myaveres, dwlim, uplim)
> & mytag == 1, msymbol(oh))
> (line uplim avefit, clcolor(gray) lstyle(solid))
> (line dwlim avefit, clcolor(gray) lstyle(solid))
> (scatter myaveres avefit if !inrange(myaveres, dwlim, uplim) & mytag == 1,
> mcolor(black)),
> xtitle(Average predicted mortality probability) ytitle(Average residual)
> legend(off) scheme(sj)
```

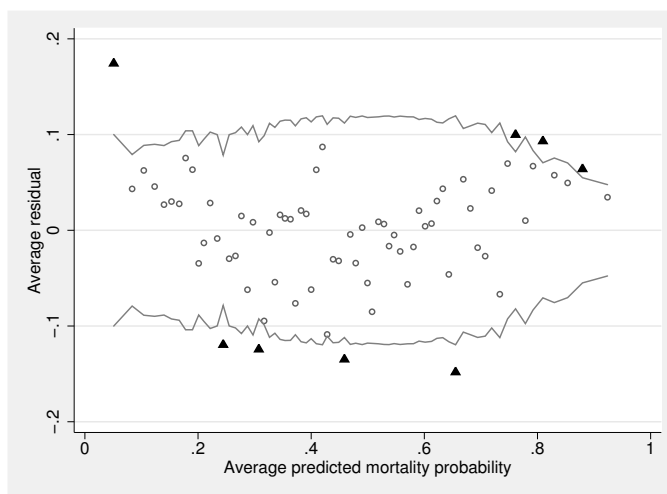


Figure 1. Binned residual plot to assess the overall fit of the model

Figure 1 displays the produced binned residual plot. There is some curvature to the pattern of binned residuals, although this is not particularly extreme. However, assessing the fit of the model with respect to x_1 does indicate problems.

```
. keep y x1 x2 pred_y resid
. sort x1
. generate myids = _n if pred_y < .
. local nbins = floor(sqrt(5000))
. egen binno = cut(myids) if pred_y < . , group(`nbins`) icodes
. egen avex1 = mean(x1), by(binno)
. egen myaveres = mean(resid), by(binno)
. egen mysd = sd(resid), by(binno)
. egen mytag = tag(binno)
. bysort binno: egen binsize = count(pred_y)
. generate uplim = 2*mysd/sqrt(binsize)
. generate dwlim = -2*mysd/sqrt(binsize)
. graph twoway (scatter myaveres avex1 if inrange(myaveres, dwlim, uplim) &
> mytag == 1, msymbol(oh))
> (line uplim avex1, clcolor(gray) lstyle(solid))
> (line dwlim avex1, clcolor(gray) lstyle(solid))
> (scatter myaveres avex1 if !inrange(myaveres, dwlim, uplim) & mytag == 1,
> mcolor(black)),
> xtitle(Average x1) ytitle(Average residual) legend(off) scheme(sj)
```

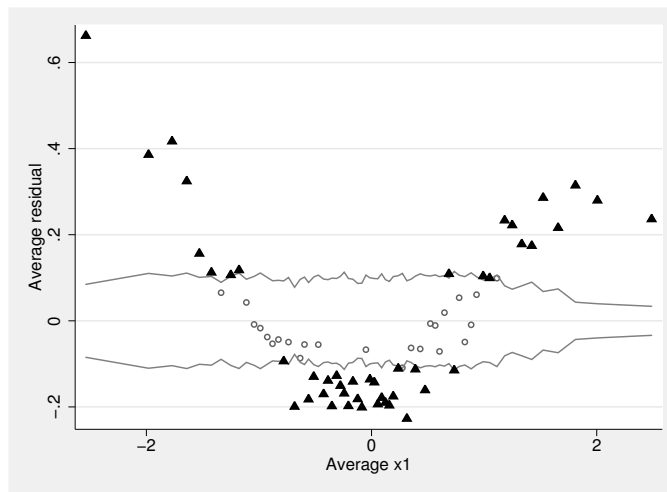


Figure 2. Binned residual plot to assess the fit of x_1

The systematic pattern in figure 2 indicates that nonlinear terms for x_1 should be included in the logistic regression model. We fit the model including a quadratic term for x_1 as follows:

```
. keep y x1 x2
. qui logit y x1 x2 c.x1#c.x1 c.x2#c.x2
. predict pred_y
(option pr assumed; Pr(y))
. generate resid = y - pred_y
```

For this model, binned residual plots are constructed as above and displayed in figure 3. As is expected, a few points lie outside the confidence limits, but there are no systematic patterns in the plots.

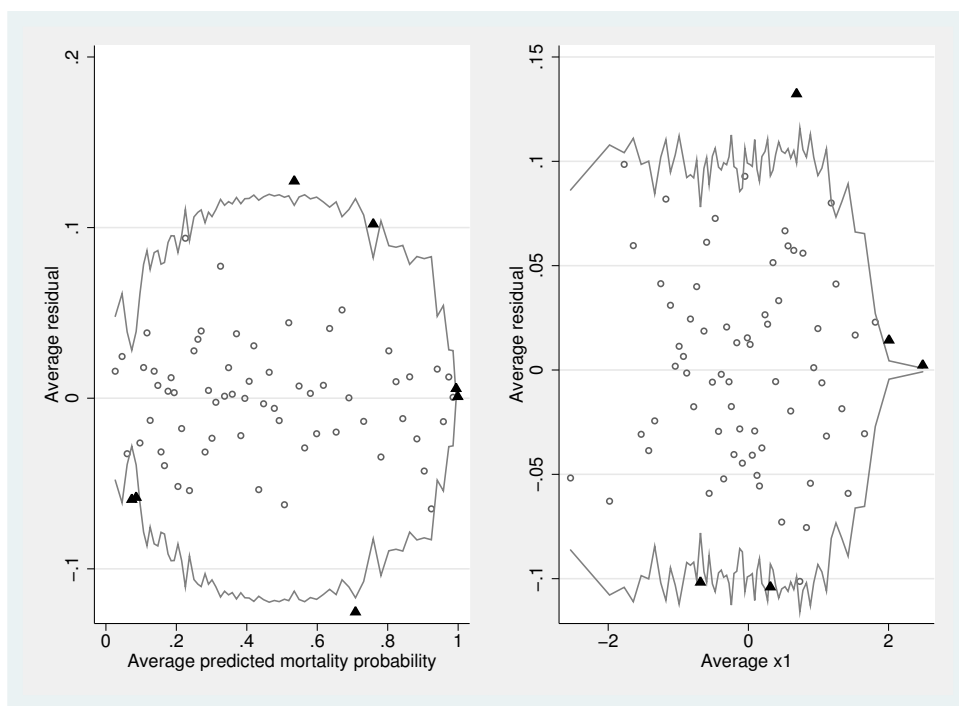


Figure 3. Binned residual plots for the model containing a quadratic term for x_1

To illustrate the usefulness of binned residual plots, we consider the Medpar dataset from Hilbe (2009), available at <http://www.crcpress.com/product/isbn/9781420075755>. This dataset is a subset of the 1991 U.S. national Medicare inpatient hospital database for Arizona, and it consists of data from 1,495 randomly selected patients. The first model for in-hospital mortality included length of hospital stay, indicators for age over 80 years, and type of surgery (elective, urgent, or emergency, with elective as baseline):

```

. use medpar.dta, clear
. quietly logit died los age80 type2 type3
. predict pred_y, pr
. generate resid = died - pred_y
. sort pred_y, stable

```

Binned residual plots to assess the overall fit and the inclusion of length of stay were constructed and are displayed in the first row of figure 4. Because many patients have identical estimated mortality probabilities, the `stable` option of the `sort` command should be used.

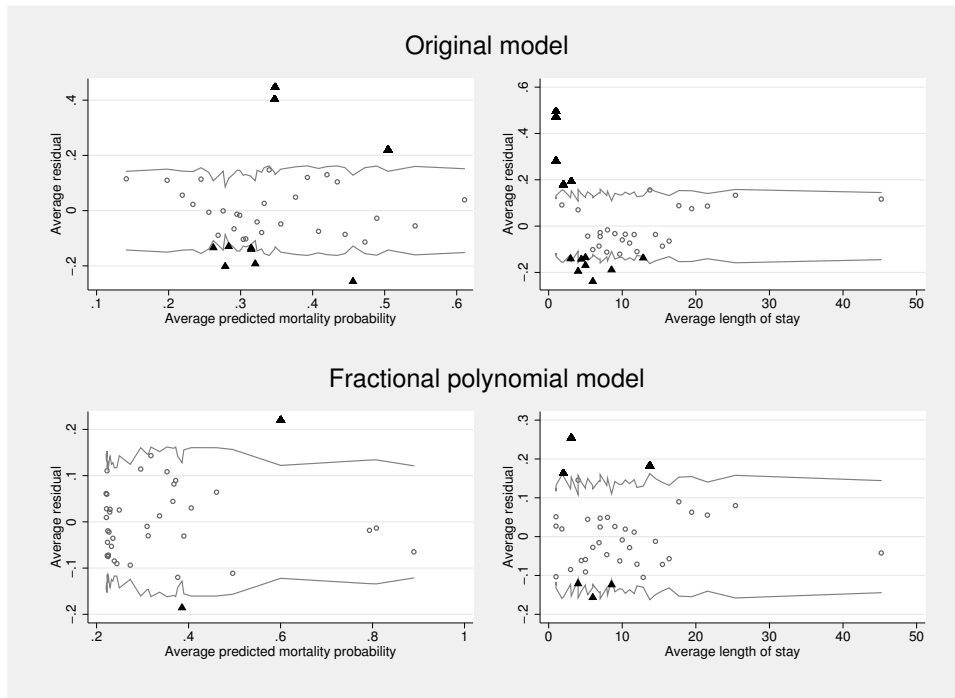


Figure 4. Binned residual plots for the Medpar example

The binned residual plot for length of stay indicates that a linear term for length of stay does not accurately capture the relationship between mortality and length of stay. A multivariable fractional polynomial logistic model is fit as follows:

```

. quietly mfp logit died los age80 type2 type3

```

The selected model contains indicators for age over 80 years and type of surgery, and a degree-1 fractional polynomial for length of stay with power -2 . Binned residual plots to assess the overall fit and length of stay are displayed in the second row of figure 4. These plots indicate that this model is a much better fit to the data than that containing a linear term for length of stay.

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- Gelman, A., and J. Hill. 2007. *Data Analysis Using Regression and Multi-level/Hierarchical Models*. Cambridge: Cambridge University Press.
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