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A NOTE ON BAYESIAN SIMULTANEOUS LINEAR
REGRESSION WITH CONSTANT SLOPES

BY

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A Note on Bayesian Simultaneous Linear Regression
with Constant Slopes*

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Abstract

This paper refines and extends the work of Shigemasu(1976) on simultaneous estimation of regressions in m groups. The posterior model estimation equations are restated in terms of sufficient statistics thus reducing the amount of computation required at each iteration and the amount of computer storage required. New estimates from marginal modes are also provided. The work is also extended to the two-way layout.

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Introduction

Shigemasu (1976) provided a Bayesian treatment of simultaneous regression in m groups with multiple predictors. Specifically, he simplified an earlier Bayesian analysis of this problem (Jackson, Novick, and Thayer, 1971) by assuming homogeneity (across groups) of within-group regression slopes. He retained a Model II (exchangeability) assumption only with regard to group intercepts. Shigemasu also extended the analysis to include a two-way layout for the groups with Model III (mixed model) assumptions for the intercepts. For both of these cases, he derived joint modal estimates for the relevant model parameters (including slopes, intercepts, and residual variance). The reader is referred to Shigemasu's paper for a discussion of the applicability of these models to educational situations and for examples of the success of the modal estimates in cross-validation. The purpose of the present note is to simplify the task of the data analyst in obtaining these Bayesian estimates by rewriting Shigemasu's equations in terms of sufficient statistics and to provide for some slightly modified and improved estimates based on marginalization with respect to nuisance parameters. A simple crossvalidation demonstrates the new method and its usefulness.

Regression in a one-way layout

First, Shigemasu's treatment of the one-way layout (henceforth referred to as Model II) will be considered. Following Shigemasu's notation, suppose there are m groups with n_i individuals in group i ($\sum_{i=1}^m n_i = n$), and p predictors. For individual k in group i , y_{ik} represents the criterion (or dependent variable) score, and $x_{ik\ell}$ ($\ell = 1, \dots, p$) represent the predictor (or independent variable) scores. The sufficient statistics for Shigemasu's Model II analysis are the group means and pooled within-group sums of squares and cross products for the criterion and predictors. Specifically, the group means required are $y_{i.}$ and $x_{i.\ell}$ for $i = 1, \dots, m$; and $\ell = 1, \dots, p$. The sums of squares and cross products needed are

$$S_{yy} = \sum_{i=1}^m \sum_{k=1}^{n_i} (y_{ik} - y_{i.})^2, \quad S_{y\ell} = \sum_{i=1}^m \sum_{k=1}^{n_i} (y_{ik} - y_{i.})(x_{ik} - x_{i.\ell}),$$

and

$$S_{\ell\ell'} = \sum_{i=1}^m \sum_{k=1}^{n_i} (x_{ik} - x_{i.\ell})(x_{ik\ell'} - x_{i.\ell'}) \text{ for } \ell, \ell' = 1, \dots, p.$$

Shigemasu's Model II, as given in his equation (1), (p. 159)

is

$$y_{ik} = \alpha_i + \sum_{\ell=1}^p x_{ik} \beta_{\ell} + e_{ik} \text{ for } i = 1, \dots, m, \text{ and } k = 1, \dots, n_i.$$

The variance component associated with the α_i is denoted by ϕ_{α} , and the component associated with e_{ik} (i.e., the residual variance) is denoted by ϕ . Taking the standard structural and indifference prior distribution assumptions and denoting the components of the joint modal estimate for the parameters of this model as $\tilde{\alpha}_i$, $\tilde{\beta}_{\ell}$, $\tilde{\phi}_{\alpha}$, and $\tilde{\phi}$, these may be obtained iteratively as follows:

1. Use the least squares estimates for α_i and β_ℓ as a starting point.

Specifically, start with $\tilde{\beta}_\ell$ as the solution to the equations

$$\sum_{\ell=1}^P \tilde{\beta}_\ell S_{\ell\ell'} = S_{y\ell'}, \text{ for } \ell' = 1, \dots, P,$$

and let

$$\tilde{\alpha}_i = y_{i.} - \sum_{\ell=1}^P \tilde{\beta}_\ell x_{i.l} \text{ for } i = 1, \dots, m.$$

2. Take the value of $\tilde{\phi}_\alpha$ to be

$$\tilde{\phi}_\alpha = [\lambda_\alpha + \sum_{i=1}^m (\tilde{\alpha}_i - \tilde{\alpha}_i)^2] / (v_\alpha + m + 1),$$

where λ_α and v_α summarize prior beliefs concerning ϕ_α (see Shigemasu, 1976, p. 161).

3. Take the value of $\tilde{\phi}$ to be

$$\begin{aligned} \tilde{\phi} = [v + n + 2]^{-1} & \left[\lambda + \sum_{\ell=1}^P \sum_{\ell'=1}^P (\tilde{\beta}_\ell \tilde{\beta}_{\ell'} S_{\ell\ell'}) - 2 \sum_{\ell=1}^P (\tilde{\beta}_\ell S_{y\ell}) + S_{yy} \right. \\ & \left. + \sum_{i=1}^m n_i (y_{i.} - \tilde{\alpha}_i - \sum_{\ell=1}^P \tilde{\beta}_\ell x_{i.l})^2 \right] \end{aligned}$$

As before, λ and v summarize prior beliefs, this time concerning ϕ , and are discussed by Shigemasu (p. 161). On the first iteration only, $\tilde{\phi}$ can be obtained from the simpler expression

$$\tilde{\phi} = [\lambda - \sum_{\ell=1}^P \tilde{\beta}_\ell S_{y\ell} + S_{yy}] / [v + n + 2].$$

4. Find new values for $\tilde{\alpha}_i$ and $\tilde{\beta}$ by first obtaining

$$w_i = \tilde{\phi}_\alpha / (\tilde{\phi}_\alpha + \tilde{\phi} / n_i) \text{ for } i = 1, \dots, m.$$

Then take

$$\tilde{y}_{..} = \frac{\sum_{i=1}^m (w_i y_{i.})}{\sum_{i=1}^m w_i}$$

and

$$\tilde{x}_{..l} = \frac{\sum_{i=1}^m (w_i x_{i.l})}{\sum_{i=1}^m w_i} \text{ for } l = 1, \dots, P.$$

These are weighted averages of the group means. Let $\tilde{\beta}_\ell$ be the solution of the equations

$$\begin{aligned} \sum_{\ell=1}^p \tilde{\beta}_\ell [S_{\ell\ell'} + (\tilde{\phi}/\tilde{\phi}_\alpha) \sum_{i=1}^m w_i (x_{i. \ell} - \tilde{x}_{.. \ell})(x_{i. \ell'} - \tilde{x}_{.. \ell'})] \\ = S_{y\ell'} + (\tilde{\phi}/\tilde{\phi}_\alpha) \sum_{i=1}^m w_i (y_{i.} - \tilde{y}_{..})(x_{i. \ell'} - \tilde{x}_{.. \ell'}) \text{ for } \ell' = 1, \dots, p. \end{aligned}$$

Then $\tilde{\alpha}_i$ are given by

$$\tilde{\alpha}_i = w_i (y_{i.} - \sum_{\ell=1}^p \tilde{\beta}_\ell x_{i. \ell}) + (1 - w_i) (\tilde{y}_{..} - \sum_{\ell=1}^p \tilde{\beta}_\ell \tilde{x}_{.. \ell}).$$

Taking these values for $\tilde{\alpha}_i$ and $\tilde{\beta}_\ell$, return to step 2. The procedure should be repeated until the values for $\tilde{\phi}$ and $\tilde{\phi}_\alpha$ have stabilized. In application, convergence typically occurs in five iterations or less.

The equations given above for $\tilde{\alpha}_i$ and $\tilde{\phi}_\alpha$ are taken directly from (10) and (12), respectively, given by Shigemasu on p. 163. The present equations for $\tilde{\beta}_\ell$ and $\tilde{\phi}$ are based on Shigemasu's (6), (9), and (11), but required some algebraic manipulation to achieve a form involving only sufficient statistics.

It should be emphasized that $\tilde{\alpha}_i$, $\tilde{\beta}_\ell$, $\tilde{\phi}$, and $\tilde{\phi}_\alpha$ are joint modal estimates. Thus, they are appropriate when the investigator is simultaneously interested in all the parameters and has a 0-1 loss function (a miss is as good as a mile) in mind. However, with very little effort, the above estimation procedure can be modified to provide modal estimates for various subsets of the parameters when the remaining parameters are not of primary interest.

Briefly, one begins with the joint posterior distribution of all the parameters [given by Shigemasu in (3), p. 162] and integrates with respect to the parameters one does not wish to estimate. Then one differentiates the result with respect to the remaining parameters, sets these expressions equal to zero, and solves the resulting equations for the parameters of interest.

While this may sound rather involved, the results are simple to relate: If ϕ_α is not of interest, subtract 2 from the denominator of the expression for $\tilde{\phi}_\alpha$ and continue as before. (Except, of course, that the final value of $\tilde{\phi}_\alpha$ should not be reported). If ϕ is not of interest, subtract 2 from the denominator of the expression for $\tilde{\phi}$ (and ignore the final value of $\tilde{\phi}$). If the β_{ρ} are not of interest, subtract p from the denominator of $\tilde{\phi}$ (and disregard the final values of $\tilde{\beta}_{\rho}$). The above three results may be used in any combination. Thus, if one were only interested in the joint modal estimates of the α_1 , the denominator for $\tilde{\phi}_\alpha$ should be $v_\alpha + m - 1$ and the denominator for $\tilde{\phi}$ should be $v + n - p$. With these changes, the steps given earlier should be followed exactly, but only the final values of the $\tilde{\alpha}_1$ should be reported.

In application to simultaneous regression, primary interest focuses on estimation of the slopes and intercepts within each group. It is these parameter estimates that will be used for prediction as if they are the correct values. Therefore decision theory suggests that ϕ_α and ϕ are

nuisance parameters for this decision problem. Therefore it is suggested that the marginalization with respect to these parameters be done routinely. In such applications, ϕ_α itself is of little interest and an estimate of ϕ can be obtained from its marginal distribution.

In the list given above, marginalization with respect to the α_i is not included, due to the algebraic complications involved. This is not seen as a major difficulty, since it seems unlikely that an investigator would wish to disregard group differences in reporting the results of a study for which an m-group analysis was appropriate.

Shigemasu extends the simple m-group regression model to a two-way layout. Still assuming homogeneity of regression coefficients across all groups, he adopts Model III (mixed model) assumptions concerning the intercepts. As before, the modal equations he obtains can be rewritten in terms of sufficient statistics, although the resulting expressions are more complex. They will be given here in raw score matrix form, following closely the notation used by Shigemasu on pp. 164-168 and especially relying on his equations (18)-(25). The reader is referred to Shigemasu (pp. 164-166) for a development of the model and definitions of the symbols used below.

Sufficient statistics for the Model III case may be written in Shigemasu's notation as

- G'G (diagonal matrix of cell sizes),
- G'y (vector of cell sums for the criterion variable),

$G'X$ (matrix of cell sums for the predictors),

$X'X$ (matrix of raw sums of squares and cross products for the predictors),

$X'y$ (vector of raw cross products for predictors and criterion), and

$y'y$ (raw sum of squares for criterion)

To carry out the iterative procedure for obtaining joint modal estimates of β , τ , α , γ , ϕ , ϕ_α , and ϕ_δ , begin by taking $\tilde{\phi} = 0$, $\tilde{\phi}_\alpha = 1$, and $\tilde{\phi}_\delta = .01$, say. Then obtain the following quantities:

$$1. \quad V = (G'G) + (\phi/\phi_\delta)(I_m - m^{-1}11') \otimes (I_t - \frac{\phi_\alpha}{\phi_\delta + t\phi_\alpha} 11')$$

(NOTE: On the first iteration, V is just $G'G$.)

$$2. \quad \tilde{\beta} = [(X'X) - (G'X)'V^{-1}(G'X)]^{-1}[X'y - (G'X)'V^{-1}G'y],$$

$$3. \quad \tilde{\tau} = V^{-1}[(G'y) - (G'X)\tilde{\beta}],$$

$$4. \quad \tilde{\phi} = [\lambda + (y'y) - 2\tilde{\tau}'(G'y) - 2\tilde{\beta}'(X'y) + \tilde{\tau}'(G'G)\tilde{\tau} + 2\tilde{\tau}'(G'X)\tilde{\beta} + \tilde{\beta}'(X'X)] / (v+n+2),$$

$$5. \quad \tilde{\alpha}_1 = [t\tilde{\phi}_\alpha / (t\tilde{\phi}_\alpha + \tilde{\phi}_\delta)](\tilde{\tau}_{1.} - \tilde{\tau}_{..}),$$

$$\text{where } \tilde{\tau}_{1.} = t^{-1}\sum_{ij}\tilde{\tau}_{ij} \text{ and } \tilde{\tau}_{..} = t^{-1}m^{-1}\sum_{ij}\tilde{\tau}_{ij},$$

$$6. \quad \tilde{\gamma}_j = \tilde{\tau}_{.j} = m^{-1}\sum_{ij}\tilde{\tau}_{ij},$$

$$7. \quad \tilde{\phi}_\alpha = (\lambda_\alpha + \sum_{i1}\tilde{\alpha}_i^2) / (v_\alpha + m + 2),$$

$$8. \quad \tilde{\phi}_\delta = (\lambda_\delta + \sum_{ij}\tilde{\tau}_{ij} - \tilde{\alpha}_1 - \tilde{\gamma}_j)^2 / (v_\delta + tm + 2),$$

and return to step 1.

This procedure should be continued until the values for $\tilde{\phi}$, $\tilde{\phi}_\alpha$, and $\tilde{\phi}_\delta$ have stabilized.

If one is interested in estimating the interaction terms (δ_{ij}) instead of the overall cell intercepts (τ_{ij}), the new joint modal values are given in terms of the old ones as

$$\tilde{\delta}_{ij} = \bar{\tau}_{ij} - \bar{\alpha}_i - \bar{\gamma}_j .$$

As with the one-way model, some marginalizations are easily carried out. To eliminate any of the variance components ϕ , ϕ_α , or ϕ_δ from consideration, merely reduce the relevant denominator by 2. Removing β , as before, reduces the denominator of $\tilde{\phi}$ by p . Marginalization with respect to τ , α , or γ would introduce formidable algebraic complications and, consequently, is not considered.

Finally, it should be noted that although Shigemasu (pp. 160, 166) develops both his models with each predictor centered at its respective grand mean, such a centering is not necessary for solving the modal equations. Thus, if raw predictor scores are used, the intercepts obtained correspond to the original origin for the predictors. Centered predictor scores, on the other hand, give rise to intercepts relative to the overall predictor centroid. Consequently, the investigator's choice of origin for the predictors should be guided primarily by considerations of interpretability of the resulting group intercepts.

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