

October, 2015. Incomplete Draft. Please do not cite without permission.

Insensitivity of Predictive Accuracy for Selecting among Multilevel Models

Wei Wang

Columbia University

ww2243@columbia.edu

Models selection is an integral part of any data analysis. In an ideal world, iteratively improving and comparing model fits of different specifications should be the routine of all statistical procedures, especially when developments in methodology and computation facilitate evermore sophisticated and complex models. Often, the most important question is not that whether a more complicated model is computational tractable, but why this model is an improvement over the older and simpler ones. Multilevel models (also known as Hierarchical Models) are an example of modern statistical models, which specifically handles data with group structure, for example, a national survey data with geographic and demographic information or an educational intervention applied to different schools and neighborhoods.

The gold standard of model comparison is out-of-sample prediction accuracy, i.e., in the hypothetical case of more observations coming in, which model gives the best prediction of new case of outcomes based on new cases of predictors. Cross-validation is a perhaps the most widely-used method for estimating out-of-sample prediction error and comparison of statistical models. By fitting the model on the training data set and then evaluating it on the hold-out testing set, the

over-optimism of using data twice is avoided. Furthermore, attempts have been made to use cross-validated objective functions for statistical inference (Craven and Wahba 1978; Seeger 2008), thus integrating out-of-sample prediction error estimation and model selection into one step.

In this chapter, I will discuss several challenges I encounter in using cross-validation predictive accuracy in evaluating and selecting among multilevel models, specifically in binary classification models. The first challenge is the lack of clear protocol for the cross-validation procedure: to truly test the model, the holdout set cannot be a simple random sample of the data but instead needs to have some multilevel structure itself, so that entire groups as well as individual observations are held out. Hierarchical cross-validation can be performed in the context of particular applications (Price, Nero, and Gelman 1996) but it is not clear how best to subsample structured data for cross-validation in a general way. The second challenge is that, in multilevel models, the observed loss function for data-level cross-validation can be so close to flat that the cross-validation estimates of prediction errors under candidate models can be swamped by random fluctuations.

I focus on the second of these concerns, demonstrating the limitations of prediction error in the context of a set of multilevel models fit to a large cross-tabulated national survey. An innovative aspect of this analysis is that I evaluate separately on 71 different survey responses, taking each in turn as the outcome in a comparison of regression models. This allows us to construct a relatively large corpus of data out of a single survey.

This chapter is a joint work with Andrew Gelman, and is published in (Wang and Gelman 2014).

MULTILEVEL MODELS AND SURVEY RESEARCH

There are two types of survey researchers, as identified by the classic book “Survey Errors and Survey Costs” (Groves 2004), the *describers*, who “use surveys to describe characteristics of a fixed population”, and the *modelers*, who “seek to identify causes of phenomena constantly occurring in a society”. The latter group developed models to generate less biased estimates, as a result of using more data and handling more inherent structure within the data. Multilevel models, an example of the *modeler* approach, are effective in survey research, as partial pooling can yield accurate state-level estimates from national polls (Gelman and Hill 2007). Multilevel models have been successfully applied both

to representative and nonrepresentative surveys to obtain accurate small-area estimation and prediction (Fay and Herriot 1979; Ghitza and Gelman 2013; Lax and Phillips 2009; Wang et al. 2014), and the practical application of such methods is currently being actively discussed in social science research (Buttice and Highton 2013; Lax and Phillips 2013). In this chapter, I conduct model selection procedures based on k -fold cross-validation and find that under this framework, the improvement of multilevel models over classical models is surprisingly small when measured on the scale of prediction error. Furthermore, I demonstrate that this lack of notable improvement is related to the sample size and data structure by repeating the analysis on simulated data sets that vary in terms of these two factors.

The results illustrate that under multilevel structure, it could be tricky to use cross-validation in model selection, as the size of the data and how balanced the structure is heavily affect the relative performance of the models.

In the next section, I will present a fully Bayesian model comparison framework, a preparation for the real data analysis.

MODEL ASSESSMENT AND SELECTION VIA CROSS-VALIDATION

Predictive Loss

I start with a loss function $l(\tilde{y}, a)$ corresponding to the inferential action a_M based on a model M , in face of future observations \tilde{y} . The available data, typically consisting of predictors x and outcomes y , are labeled as D . The corresponding predictive loss is then,

$$PL(p^t, M, D) = E_{p^t} l(\tilde{y}, a_M) = \int l(\tilde{y}, a_M) p^t(\tilde{y}) d\tilde{y} \quad (1)$$

where $p^t(\cdot)$ is the true distribution from which the future observations \tilde{y} are generated.

The predictive loss is affected by the form of the action a_M , the loss function l , and the data D . For example, a_M could be the mean of the posterior predictive distribution and l the mean square error loss. However, it is often convenient and theoretically desirable to use the whole posterior predictive distribution as the inferential action and a logarithmic loss function. In addition, using the whole posterior predictive distribution has a Bayesian justification, as it reflects the

full inferential uncertainty conditional on the model (Vehtari and Ojanen 2012). Substituting the choice of a_M and l into (1) yields,

$$\begin{aligned} PL(p^t, M, D) &= E_{p^t}[-\log p(\tilde{y}|D, M)] \\ &= - \int p^t(\tilde{y}) \log p(\tilde{y}|D, M) d\tilde{y} \end{aligned} \quad (2)$$

This quantity is central to predictive model selection. The fundamental difficulty in estimating it is that the true distribution $p^t(\cdot)$ is unknown.

Another important quantity arises when I approximate the true distribution with the empirical distribution, which gives the training loss,

$$\begin{aligned} TL(M, D) &= - \int \log p(y|D, M) d\hat{F}(y) \\ &= - \frac{1}{N} \sum_{y \in D} \log p(y|D, M). \end{aligned} \quad (3)$$

The training loss uses the same data for both estimation and evaluation and so in general underestimates prediction error.

Prediction Error

With (2), the model selection task is straightforward. Among the candidate models, the best model under this framework is the one that minimizes the predictive loss:

$$- \min_M \int p^t(\tilde{y}) \log p(\tilde{y}|D, M) d\tilde{y}, \quad (4)$$

which has a lower bound, $-\int p^t(\tilde{y}) \log p^t(\tilde{y}) d\tilde{y}$, which is the entropy of the true distribution. It is often more informative to look at the excess of the predictive loss over this lower bound, as shown in (5). I label this quantity as the prediction error. Conceptually, the prediction error indicates how far the posterior predictive distribution is from the oracle, and it is the Kullback-Leibler divergence between the posterior predictive distribution of the candidate model and the true generative model. As its form suggests, the prediction error is the difference between log posterior predictive density and log true predictive density, averaged over the true predictive distribution,

$$\begin{aligned}
PE(p^t, M, D) &= PL(p^t, M, D) - LB(p^t) \\
&= - \int p^t(\tilde{y}) \log p(\tilde{y}|D, M) d\tilde{y} + \int p^t(\tilde{y}) \log p^t(\tilde{y}) d\tilde{y}.
\end{aligned} \tag{5}$$

So to estimate the prediction error, I need to estimate the two terms in (5).

k-fold Cross-Validation for Estimating Predictive Loss

In the predictive framework, the central obstacle of estimating the predictive loss (2) is that the future observations are not available. One thread of research attempts to estimate and correct the bias introduced by reusing the sample and thus gives rise to various information criteria, whose validity hinges on a number of assumptions and simplifications. Another thread of research is to use hold-out data for testing, thus making training and testing data independent. This leads to a variety of resampling procedures, including leave-one-out cross-validation, k -fold cross-validation, Monte Carlo cross-validation, and bootstrapping. In practice, k -fold cross-validation is popular due to its computational convenience and stability (Kale, Kumar, and Vassilvitskii 2011). Formally, the k -fold cross-validation of the predictive loss is given by

$$\begin{aligned}
\widehat{PL}^{\text{cv}}(M, D) &= - \frac{1}{N} \sum_{k=1}^K \sum_{i \in \text{test}_k} \log p(y_i | D^k, M) \\
&= - \frac{1}{N} \sum_{i=1}^N \log p(y_i | D^{(\setminus i)}, M),
\end{aligned} \tag{6}$$

where D^k represents the k^{th} training set, test_k represents the k^{th} testing set under the random partition and $D^{(\setminus i)}$ denotes the training set that excludes the i^{th} observation. Because k -fold cross-validation does not use all the data, the prediction error estimates are biased, but in the cases where there are relatively few predictors, this bias is small (Burman 1989).

The practical impediment of using cross-validation is the computational burden: with k -fold cross-validation, I need to fit the model k times. However, in many cases it is possible to perform the k steps in parallel.

The problem remains of estimating the second term in (5), namely the lower bound of predictive loss. In this chapter, I use the in-sample training loss

$TL(M_s, D)$ of the saturated model M_s as the surrogate for the lower bound. So the estimated prediction error is

$$\begin{aligned}\widehat{PE}(M, D) &= \widehat{PL}^{\text{cv}}(M, D) - TL(M_s, D) \\ &= -\frac{1}{N} \sum_{i=1}^N \log p(y_i | D^{(\setminus i)}, M) + \frac{1}{N} \sum_{y \in D} \log p(y | D, M_s).\end{aligned}\tag{7}$$

CROSS-VALIDATION OF STRUCTURED DATA

Standard cross-validation assumes that data are independent and with no distributional differences between the training and testing sets. For structured data, it is not always clear how best to perform this partition. (Burman, Chow, and Nolan 1994) discusses a modification of ordinary cross-validation procedure for stationary time series. In this chapter, I focus on the cross-tabulated structure, which is the characteristic of survey data with discrete responses. In an unbalanced cross-tabulated data set, simple random sampling might result in undersampling of small cells. Thus, I adopt a stratified sampling approach to guarantee that each cell is partitioned into a training part and a testing part. Another possibility is to perform a cluster sampling and train the model on some cells and test the fitted model on others. This approach is related to transfer learning (Pan and Yang 2010). In the analysis of survey data, the focus is mostly on the existing cells rather than on hypothetical new cells, and so I only discuss cross-validation using stratified sampling on structured data.

COMPARING MULTILEVEL MODELS FOR BINARY SURVEY OUTCOMES

The 2006 Cooperative Congressional Election Survey, the example data set in this paper, is a national stratified sample of size 30,000 that includes a wide variety of response outcomes, thus providing an ideal setting to evaluate cross-validation. Although various demographic predictors are available in this data set, I keep this model simple by using only two predictors, state and income. Under this setting, the multilevel model is the preferred model over no pooling (saturated model) or complete pooling (additive model). On one hand, the saturated model will trigger overfitting. On the other hand, income and state are known to have

strong interactions when predicting electoral choice (Gelman et al. 2009), so the additive model must be substantively inadequate.

Complete Pooling, No Pooling, and Partial Pooling Models

Bayesian multilevel modeling is a natural choice for analyzing cross-tabulated data. When the data provide many explanatory variables, and thus a potentially complex cross-tabulated structure, it is difficult to model the interactions among explanatory variables in classical models, since each single cell is getting sparser and the estimates become unstable. By borrowing strength across cells, a multi-level model (or, alternatively, some other structured model such as a Gaussian process) can produce stable estimates even for cells that have few observations and thus can be viewed as a multivariate regression or interpolation procedure..

I develop this model on a simple two-way cross-tabulation of survey data, with state and income as the two explanatory variables, having J_1 and J_2 levels respectively.¹ I assume no continuous predictors in this model. Let N be the total sample size of the survey, then the array of cell counts follows a multinomial distribution,

$$\mathbf{N} \sim \text{Multinomial}(N, \mathbf{p})$$

, where

$$\begin{aligned}\mathbf{N} &= (N_{j_1 j_2})_{J_1 \times J_2}, \\ \mathbf{p} &= (p_{j_1 j_2})_{J_1 \times J_2}.\end{aligned}$$

The population is thus divided into $J_1 \times J_2$ cells. I constrain the discussion to binary outcomes. Then for a respondent in cell (j_1, j_2) , the probability that he or she gives a positive response is $\pi_{j_1 j_2}$, which is modeled using logistic regression:

$$\text{logit}(\pi_{j_1 j_2}) = \mathbf{Z}\boldsymbol{\beta},$$

in which \mathbf{Z} is the covariate vector and $\boldsymbol{\beta}$ includes the main and interaction effects. Since the goal of inference is on cell proportions $\pi_{j_1 j_2}$ rather than cell assignment probabilities $p_{j_1 j_2}$, I treat $p_{j_1 j_2}$ as fixed throughout.

Under this setup, I consider three models:

¹For the 2006 Cooperative Congressional Election Survey data set, there are 50 states ($J_1 = 50$), and 5 income levels ($J_2 = 5$), including less than \$20,000, \$20,000-\$40,000, \$40,000-\$75,000, \$75,000-\$150,000, and \$150,000+.

- Complete pooling of interactions:

$$\pi_{j_1 j_2} = \text{logit}^{-1} (\beta_{j_1}^{\text{state}} + \beta_{j_2}^{\text{inc}})$$

- No pooling:

$$\pi_{j_1 j_2} = \text{logit}^{-1} (\beta_{j_1}^{\text{state}} + \beta_{j_2}^{\text{inc}} + \beta_{j_1 j_2}^{\text{state*inc}})$$

- Partial pooling:

$$\pi_{j_1 j_2} = \text{logit}^{-1} (\beta_{j_1}^{\text{state}} + \beta_{j_2}^{\text{inc}} + \beta_{j_1 j_2}^{\text{state*inc}})$$

with $\beta_{j_1 j_2}^{\text{state*inc}} \stackrel{i.i.d.}{\sim} N(0, \sigma^2)$ where the scale parameter σ is estimated from the data (with a separate value for each survey outcome).

Although nonparametric multilevel modeling, both in the Bayesian (Hjort 2010) and the frequentist (Ruppert, Wand, and Carroll 2003) perspectives, have been under rapid development, I adopt a linear parametric specification for the multilevel model, because linear parametric models are still the standard specification, and software that fit the routine linear parametric models are widely available and easily accessible to practitioners. In the remaining sections of this chapter, I compare the prediction error of these three models under various real data and simulation settings.

Multilevel models in big-data applications can be much more complicated (Ghitza and Gelman 2013); I use a relatively simple example here to explore the basic ideas.

Computation

Ideally I want to do full Bayesian inference on the model, but for computational reasons I am currently using an approximate marginal posterior mode estimate provided by `blme` (Dorie 2013) in R, which is an extension of the widely-used `lme4` (Bates, Maechler, and Bolker 2013) package. The `lme4` package approximately integrates out the random effects to obtain an approximate marginal MLE of the scale parameter and the fixed effects. However, modal estimates can end up on the boundary due to sampling variability (Chung et al. 2013), which in the case makes the partial pooling model reduce to complete pooling. In `blme`, the scale parameter σ is also given a gamma prior with shape parameter 2.5 and rate parameter 0. The gamma prior is used to regularize the prior of the scale and pull the estimates of the interactions away from zero, a situation that often happens in modal estimation.

Estimation Procedure

For each outcome, I fit a multilevel logistic regression model, with additive, fully-interacted, and multilevel models. I use 5-fold cross-validation to estimate predictive loss (using more folds gives essentially identical results). I estimate the lower bound using the training loss of the saturated model.

Under the aforementioned setting, the cross-validation loss estimate is,

$$\begin{aligned}
\widehat{PL}^{\text{cv}}(M, D) &= -\frac{1}{N} \sum_{k=1}^K \sum_{j \in \text{test}_k} \log p(y_j | D^k, M) \\
&= -\frac{1}{N} \sum_{k=1}^K \sum_{i,j} [y_{ij}^{\text{test}_k} \log \hat{\pi}_{ij}^{D^k} + (n_{ij}^{\text{test}_k} - y_{ij}^{\text{test}_k}) \log(1 - \hat{\pi}_{ij}^{D^k})] \\
&= -\frac{1}{N} \sum_{i,j} \sum_{k=1}^K [y_{ij}^{\text{test}_k} \log \hat{\pi}_{ij}^{D^k} + (n_{ij}^{\text{test}_k} - y_{ij}^{\text{test}_k}) \log(1 - \hat{\pi}_{ij}^{D^k})] \\
&= -\frac{1}{N} \sum_{i,j} [y_{ij} \overline{\log \hat{\pi}_{ij}} + (n_{ij} - y_{ij}) \overline{\log(1 - \hat{\pi}_{ij})}] \\
&= -\sum_{i,j} \frac{n_{ij}}{N} [\pi_{ij} \overline{\log \hat{\pi}_{ij}} + (1 - \pi_{ij}) \overline{\log(1 - \hat{\pi}_{ij})}],
\end{aligned}$$

in which $n_{ij}^{\text{test}_k}$ is the number of respondents in cell (i, j) of the k -th testing set, $y_{ij}^{\text{test}_k}$ is the number of respondents who answered yes in cell (i, j) of the k -th testing set, correspondingly, n_{ij} and y_{ij} are the numbers of total respondents and respondents who answered yes in cell (i, j) , $\hat{\pi}_{ij}^{D^k}$ is the estimated π_{ij} using the k -th training data set, and $\overline{\log \hat{\pi}_{ij}}$ is the weighted average log posterior proportion from each fold, $\left(\sum_{k=1}^K y_{ij}^{\text{test}_k} \log \hat{\pi}_{ij}^{D^k}\right) / y_{ij}$, and $\overline{\log(1 - \hat{\pi}_{ij})}$ has the similar form. The cross-validation loss estimate is approximately a measure of loss under cell proportion distribution $(\exp(\overline{\log \hat{\pi}_{ij}}), \exp(\overline{\log(1 - \hat{\pi}_{ij})}))$ (“approximately” because these two probabilities do not in general add up to 1). The quick calculation in section 1.2 suggests that I should expect to see only small improvements in cross-validation loss even from substantively important model improvements.

RESULTS

Prediction Errors for a Corpus of Outcomes

I begin by estimating the prediction errors of all outcomes in the survey. The results are shown in Figure~1. The x -axis is ordered by the in-sample training loss of the saturated model $TL(M_s, D)$, which we use as a surrogate for a lower bound of predictive loss. For complete pooling and partial pooling, the prediction error stays stable across different outcomes, while the no pooling model has huge prediction error for outcomes with small lower bounds. This finding makes sense since these are the settings where overfitting is most severe (saturated models achieve the lowest in-sample training error). However, the difference in prediction error between complete pooling and partial pooling seems negligible. Partial pooling is giving essentially the same result as complete pooling, at least according to cross-validation on individual survey responses.

This seems to suggest that partial pooling does not have enough information to estimate cell-to-cell variation, thus giving an overly conservative estimate. Indeed, when I plot the estimates of $\pi_{j_1 j_2}$ for one particular outcome, vote preference for in the congressional election (see the left panel of Figure~2), the estimates from partial pooling are almost identical to those from complete pooling. Even for populous states where, because of their large sample size, the amount of partial pooling should be small, there are no major differences between estimates from partial pooling model and estimates from complete pooling model (see the right panel of Figure~2). This pattern is consistent across different outcomes.

Although I believe partial pooling is intrinsically better than complete pooling, it seems that the given data are not sufficient for the partial pooling model to pick up the interaction and unpool the estimates appropriately. It is a result of the particular characteristics of this data set? There are three factors determining the structure of the data that might affect the extent of pooling of the model. First is the sample size. If I increase the sample size to a sufficiently large level, the partial pooling model will be able to partially pool the estimates to an appropriate amount. As sample size grows, the no pooling model will eventually have the same performance as partial pooling, and it might be interesting to see at what point the saturated model becomes acceptable. The second factor affecting the relative performance of the different models is the size of the interactions that are being estimated, and the third factor is the level of imbalance in the hierarchical structure. Survey data classified by demographic and geographic predictors are typically highly unbalanced due to the long tails of sizes typical in

taxonomic structures (Mandelbrot 1955). For example, the 2006 CCES includes 3,637 respondents from California but only 131 from Arkansas. This unbalanced structure will affect the amount of pooling performed by a multilevel model.

In the following subsections, I conduct simulations that vary sample size and the structure of the cells to investigate how these factors affect the relative performance of the three models as captured by cross-validation.

How Sample Size Changes the Dynamics

I artificially augment the data set by combining the data set with itself. New data sets with sample size that are 2, 3 and 4 times as large are generated. This augmentation still maintains the same level of interactions and cell structure as those of the original data. Then I estimate the prediction errors for all outcomes for the three models. Results are plotted in Figure~3. As I expected, as sample size grows, the prediction error of complete pooling model, which is essentially a wrong model, dominates the other two; while the prediction error of no pooling model keeps decreasing. When the sample size is 4 times as large as the original data set, no pooling model has almost the same prediction error as partial pooling model. This makes sense, since the problem of overfitting eventual goes away if there are sufficiently large sample size and fixed model structure.

These results suggest that for a fixed data structure, partial pooling decisively outperforms no pooling and complete pooling only for a certain window of sample sizes. To have a closer look at the range of the window, I look at one particular outcome, the vote preference in the upcoming election for the U.S. House of Representatives. I augment the sample size and plot the relative performance of the three models in Figure~4. Partial pooling model is noticeably better than complete pooling in this setup when the total sample size exceeds larger than 50,000. Other outcomes have similar patterns.

Balancedness of the Hierarchical Structure

One possible explanation for the steep learning curve of the partial pooling model is the highly unbalanced structure of the data. Although there are 50 states, the estimate of the covariance of the state random effects might not be reliable since some of the states have small sample sizes. To see how the balancedness of the structure affects the model, I simulate a data set based on partial pooling estimates from the original data set, but make each demographic-geographic cells of roughly the same size. The overall sample size is the same as that of the

real data. Relative performance of the three models for all outcomes is plotted in Figure~5. The graph shows that with balanced hierarchical structure, at the same sample size and amount of interaction, partial pooling kicks in much more quickly. Thus partial pooling is consistently better than complete pooling in this scenario. As in the previous analysis, I also look at the relative performance of the three models as sample size grows. The results are plotted in Figure~6.

DISCUSSION

Cross-validation is an important tool used to evaluate a wide variety of statistical methods and has been widely used in model comparison when predictive power is of concern. Some theoretical treatments have pointed out situations where cross-validation might have problems. For example, (Shao 1993) shows that, under the frequentist setting, using leave-one-out cross-validation for linear model variable selection is not consistent. However, the simplicity and transparency of cross-validation gives it a near-universal appeal. In this paper, I investigate the sensitivity of cross-validation as a model comparison instrument in a cross-tabulated multilevel survey data set.

I set up the model selection problem, considering three models for these structured data: the classical models of complete pooling and no pooling, and a Bayesian multilevel model. The multilevel model captures important interactions that are not included in the complete pooling model, while at the same time avoiding the inevitable overfitting from the no pooling model. However, the improvement of the multilevel model as given by cross-validation is surprisingly tiny, almost negligible to unsuspecting eyes. The problem is that improved fits with binary data yield minuscule improvements in log loss, in moderate sample sizes nearly indistinguishable from noise even if the improved estimates are substantively important when aggregated (for example, state-level public opinion). Simulations based on real data show that sample size and structure of the cross-tabulated cells play important roles in the relative margins of different models in cross-validation based model selection. Caution should be exercised in applying prediction error for model selection with structured data.

BIBLIOGRAPHY

- Bates, Douglas, Martin Maechler, and Ben Bolker. 2013. *Lme4: Linear Mixed-Effects Models Using S4 Classes*. <http://CRAN.R-project.org/package=lme4>.
- Burman, Prabir. 1989. "A Comparative Study of Ordinary Cross-Validation, V-Fold Cross-Validation and the Repeated Learning-Testing Methods." *Biometrika* 76(3): 503–14.
- Burman, Prabir, Edmond Chow, and Deborah Nolan. 1994. "A Cross-Validatory Method for Dependent Data." *Biometrika* 81(2): 351–58.
- Buttice, Matthew K., and Benjamin Highton. 2013. "How Does Multilevel Regression and Poststratification Perform with Conventional National Surveys?" *Political Analysis* 21(4): 449–67.
- Chung, Yeojin, Sophia Rabe-Hesketh, Vincent Dorie, Andrew Gelman, and Jingchen Liu. 2013. "A Nondegenerate Penalized Likelihood Estimator for Variance Parameters in Multilevel Models." *Psychometrika* 78(4): 685–709.
- Craven, Peter, and Grace Wahba. 1978. "Smoothing Noisy Data with Spline Functions." *Numerische Mathematik* 31(4): 377–403.
- Dorie, Vincent. 2013. *Blme: Bayesian Linear Mixed-Effects Models*. <http://CRAN.R-project.org/package=blme>.
- Fay, R. E., and R. A. Herriot. 1979. "Estimates of Income for Small Places: An Application of James-Stein Procedures to Census Data." *Journal of the American Statistical Association* 74: 269–77.
- Gelman, Andrew, and Jennifer Hill. 2007. *Data Analysis Using Regression and Multilevel/Hierarchical Models*. Cambridge University Press.
- Gelman, Andrew, David K. Park, Boris Shor, and Jeronimo Cortina. 2009. *Red State, Blue State, Rich State, Poor State: Why Americans Vote the Way They Do, Second Edition*. Princeton University Press.
- Ghitza, Yair, and Andrew Gelman. 2013. "Deep Interactions with MRP: Election Turnout and Voting Patterns Among Small Electoral Subgroups." *American Journal of Political Science* 57(3): 762–76.
- Groves, Robert M. 2004. *536 Survey Errors and Survey Costs*. John Wiley & Sons.
- Hjort, Nils Lid. 2010. *Bayesian Nonparametrics*. Cambridge University Press.
- Kale, Satyen, Ravi Kumar, and Sergei Vassilvitskii. 2011. "Cross-Validation and Mean-Square Stability." In *Innovations in Computer Science*, Tsinghua University Press, 487–95.

Lax, Jeffrey R., and Justin H. Phillips. 2009. "How Should We Estimate Public Opinion in the States?" *American Journal of Political Science* 53(1): 107–21.

———. 2013. "How Should We Estimate Sub-National Opinion Using MRP? Preliminary Findings and Recommendations." *Presented at Midwest Political Science Association*.

Mandelbrot, B. 1955. "On the Language of Taxonomy: An Outline of a 'Thermostatistical' Theory of Systems of Categories with Willis (Natural) Structure." In *Information Theory—Third London Symposium*, ed. Colin Cherry., 135–45.

Pan, Sinno Jialin, and Qiang Yang. 2010. "A Survey on Transfer Learning." *IEEE Transactions on Knowledge and Data Engineering* 22(10): 1345–59.

Price, Phillip N., Anthony V. Nero, and Andrew Gelman. 1996. "Bayesian Prediction of Mean Indoor Radon Concentrations for Minnesota Counties." *Health Physics* 71: 922–36.

Ruppert, David, Matt P Wand, and Raymond J Carroll. 2003. *Semiparametric Regression*. Cambridge University Press.

Seeger, Matthias W. 2008. "Cross-Validation Optimization for Large Scale Structured Classification Kernel Methods." *Journal of Machine Learning Research* 9: 1147–78.

Shao, Jun. 1993. "Linear Model Selection by Cross-Validation." *Journal of the American statistical Association* 88(422): 486–94.

Vehtari, Aki, and Janne Ojanen. 2012. "A Survey of Bayesian Predictive Methods for Model Assessment, Selection and Comparison." *Statistics Surveys* 6: 142–228.

Wang, Wei, and Andrew Gelman. 2014. "Difficulty of Selecting Among Multilevel Models Using Predictive Accuracy." *Statistics and Its Interface* 7: 1–8.

Wang, Wei, David Rothschild, Sharad Goel, and Andrew Gelman. 2014. "Forecasting Elections with Non-Representative Polls." *International Journal of Forecasting*.

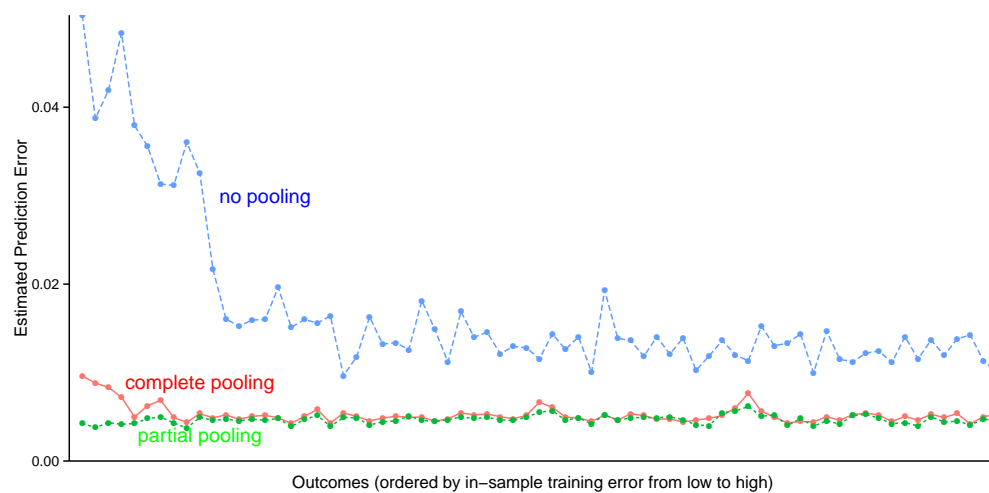


Figure 1: Measure of fit (estimated prediction error) for all response outcomes in the 2006 Cooperative Congressional Election Survey. Outcomes are ordered by the lower bound (in-sample loss of the saturated model). The no pooling model gives a bad fit. Partial pooling does best but in most cases is almost indistinguishable from complete pooling under the cross-validation criterion.

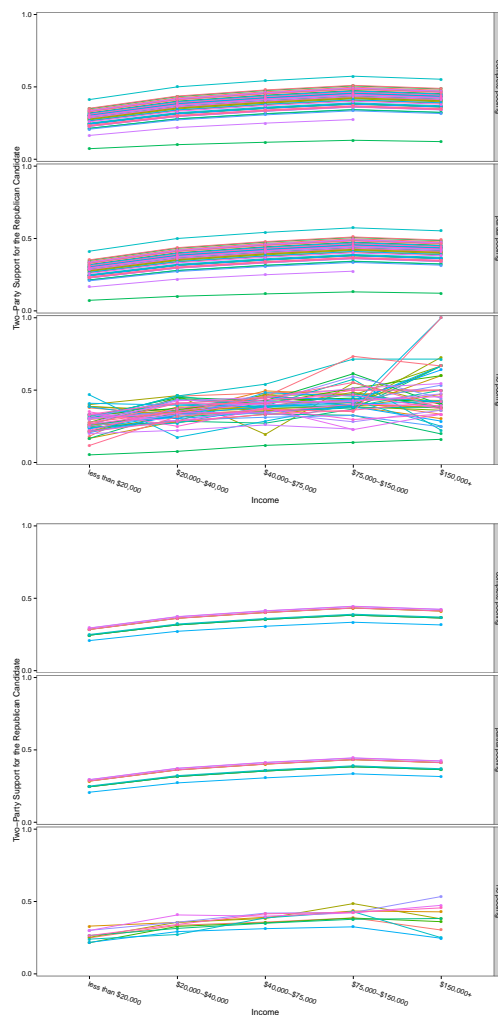


Figure 2: *Left panel: Cell proportion estimates for three models of vote intention. Each line is a state. The partial pooling model pools so much that it is indistinguishable from complete pooling. Right panel: The same estimates for the 10 most populous states. Still, partial pooling estimates are similar to complete pooling estimates.*

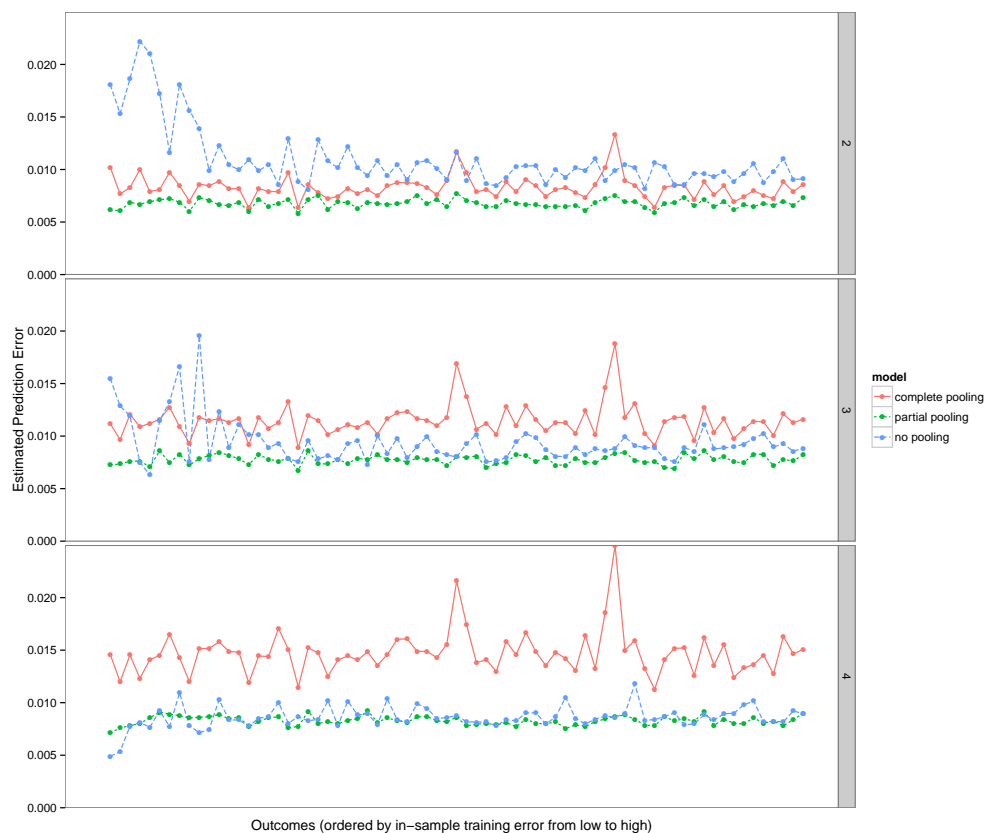


Figure 3: Estimated prediction error of all response outcomes for augmented data sets. From top to bottom, the data sets have 2, 3, and 4 times as many data points as the original data set. The outcomes are ordered by the in-sample predictive loss. As sample size grows, complete pooling gradually gets worse and no pooling gets better.

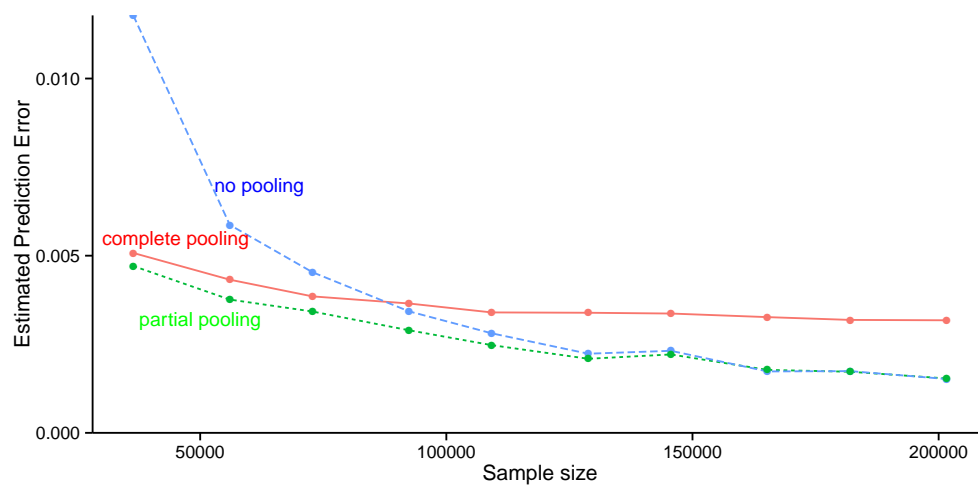


Figure 4: Prediction error of the three models as sample size grows. The outcome under consideration is partisan vote preference in the upcoming congressional election. By this criterion, partial pooling and complete pooling perform similarly until sample size exceeds 50,000.

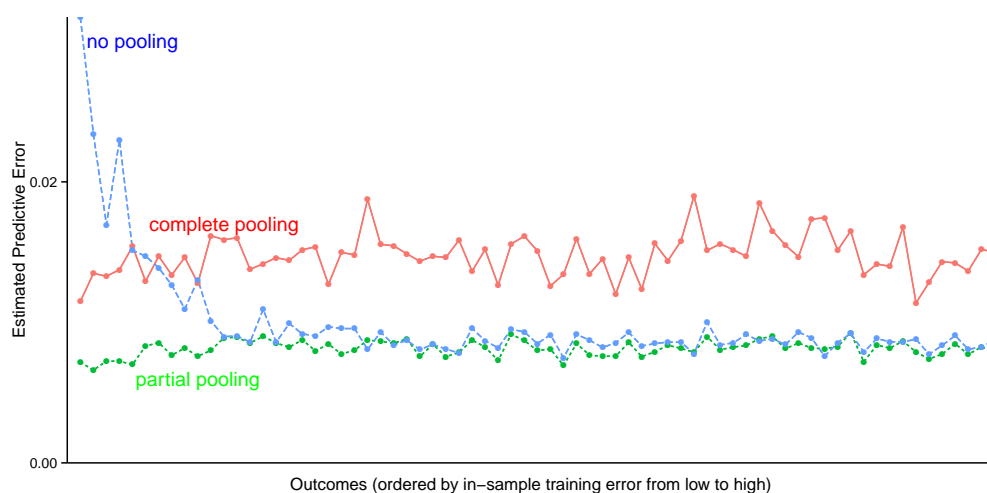


Figure 5: Measure of fit (prediction error) for all outcomes, ordered by in-sample training loss. The data set is simulated from real data set, and has the same sample size in total as the real data set, but keeping all demographic-geographic cells balanced. In this case, complete pooling model has much higher prediction errors than no pooling and partial pooling. Partial pooling is slightly but consistently better than no pooling. In particular, no pooling model has huge prediction error for outcomes that have smaller in-sample training loss.

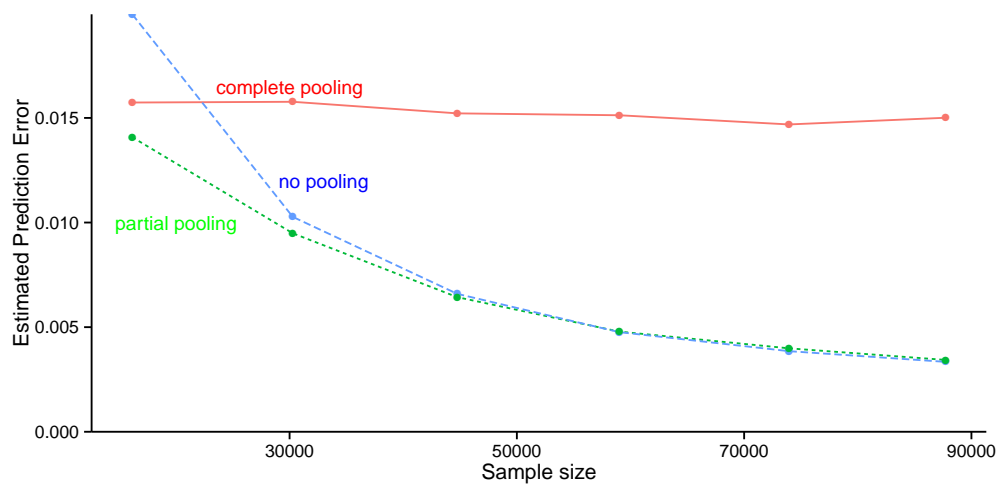


Figure 6: Prediction error of the three models as sample size grows under the simulated balanced data set. The outcome under consideration is the vote for the Republican candidate in the U.S House of Representatives. Partial pooling has the lowest prediction error when sample size is under 70,000.