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Modeling Censored Data Using Mixture Regression Models with an Application to Cattle Production Yields

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Abstract:

This research develops a mixture regression model that is shown to have advantages over the classical Tobit model in model fit and predictive tests when data are generated from a two step process. Additionally, the model is shown to allow for flexibility in distributional assumptions while nesting the classic Tobit model. A simulated data set is utilized to assess the potential loss in efficiency from model misspecification, assuming the Tobit and a zero-inflated log-normal distribution, which is derived from the generalized mixture model. Results from simulations key on the finding that the the proposed zero-inflated log-normal model clearly outperforms the Tobit model when data are generated from a two step process. When data are generated from a Tobit model, forecasts are more accurate when utilizing the Tobit model. However, the Tobit model will be shown to be a special case of the generalized mixture model. The empirical model is then applied to evaluating mortality rates in commercial cattle feedlots, both independently and as part of a system including other performance and health factors. This particular application is hypothesized to be more appropriate for the proposed model due to the high degree of censoring and skewed nature of mortality rates. The zero-inflated log-normal model clearly models and predicts with more accuracy than the Tobit model.

Keywords: censoring, livestock production, tobit, zero-inflated, bayesian

Modeling Censored Data Using Mixture Regression Models with an Application to Cattle Production Yields

Censored dependent variables have long been a complexity associated with micro data sets. The most common occurrences are found in consumption and production data. Regarding consumption, households typically do not purchase all of the goods being evaluated in every time period. Similarly, a study evaluating the number of defects in a given production process will likely have outcomes with no defects. In both cases, ordinary least squares parameter estimates will be biased when applied to these types of regressions (Amemiya, 1984).

The seminal work by Tobin (1958) was the first to recognize this bias and offer a solution that is still quite popular today. The univariate Tobit model is extended, under a mild set of assumptions, to include multivariate settings (Amemiya, 1974; Lee, 1993). While empirical applications in univariate settings are discussed by Amemiya (1984), multivariate applications are becoming more frequent (Belasco, Goodwin and Ghosh, 2007; Chavas and Kim, 2004; Cornick, Cox and Gould, 1994; Eiswerth and Shonkwiler, 2006). The assumption of normality has made the Tobit model inflexible to data generating processes outside of that major distribution (Bera et al., 1984). Additionally, Arabmazar and Schmidt (1982) demonstrate that random variables modeled by the Tobit model contain substantial bias when the true distribution is non-normal and has a high degree of censoring.

The Tobit model has been generalized to allow variables to influence the probability of a non-zero value and the non-zero value itself as two separate processes (Cragg, 1971; Jones, 1989), which are commonly referred to as the hurdle and double-hurdle models, respectively. Another model that allows for decisions or production output processes to be characterized as a two step process is the zero-inflated class of models.¹

¹When applied to continuous data, the zero-inflated and hurdle models can be generalized to be similar. As pointed

Lambert (1992) extended the classical ZIP model to include regression covariates, where covariate effects influence both ρ as well as the nonnegative outcome. Further, Li et al. (1999) developed a multivariate zero-inflated Poisson model that is motivated to evaluate production processes involving multiple defect types. More recently, Ghosh et al. (2006) introduced a flexible class of zero-inflated models that can be applied to discrete distributions within the class of power series distributions. Their study also finds that Bayesian methods have more desirable finite sample properties than maximum likelihood estimation, with their particular model.

Computationally, a Bayesian framework may have significant advantages over classical methods. In classical methods, such as maximum likelihood, parameter estimates are found through numerical optimization, which can be computationally intensive in the presence of many unknown parameter values. Alternatively, Bayesian parameter estimates are found by drawing realizations from the posterior distribution. Within large data sets the two methods are shown to be equivalent through the Bernstein-von Mises Theorem (Train, 2003). This property allows Bayesian methods to be used in place of classical methods, under certain conditions, which are asymptotically similar and may have significant computational advantages. In addition to asymptotic equivalence, Bayes estimators, in a Tobit framework, have been shown to converge faster than maximum likelihood methods (Chib, 1992).

In this study, we consider the use of a mixture model to characterize censored dependent variables as an alternative to the Tobit model. This model will be shown to nest the Tobit model, while major advantages include the flexibility in distributional assumptions and an increased efficiency in situations involving a high degree of censoring. For our empirical study, we derive the zero-inflated log-normal model from a generalized mixture model.

Data are then simulated to test the ability of each model to fit the data and predict out of

out by Gurmu and Trivedi (1996), hurdle and zero-inflated models can be thought of as refinements to models of truncation and censoring. Hurdle models typically use truncated-at-zero distributions, but are not restricted to truncated distributions. Cragg (1971) recommends the use of a log-normal distribution to characterize positive values. However, most applications of the hurdle model assume a truncated density function.

sample observations. Results from the zero-inflated mixture model will be compared to Tobit results through the use of goodness-of-fit and predictive power measures. By simulating data, the two models can be compared in situations where the data generating process is known.

In addition, a comprehensive data set will be used that includes proprietary cost and production data from five cattle feedlots in Kansas and Nebraska, amounting to over 11,000 pens of cattle during a 10 year period. Cattle mortality rates on a feedlot provide valuable insights into the profitability and performance of cattle on feed. Additionally, it is hypothesized that cattle mortality rates are more accurately characterized with a mixture model that takes into account the positive skewness of mortality rates, as well as allowing censored and non-censored observations to be modeled independently.² In both univariate and multivariate situations, the proposed mixture model more efficiently characterizes the data.

Additionally, a multivariate setting is applied to these regression models by taking into account other variables that describe the health and performance of feedlot cattle. These variables include dry matter feed conversion (DMFC), average daily gain (ADG), and veterinary costs per head (VCPH). Three unique complexities arise when modeling these four correlated yield measures. First, the conditioning variables potentially influence the mean and variance of the yield distributions. Since variance may not be constant across observations, we assume multiplicative heteroskedasticity within our model and model conditional variance as a function of the conditioning variables. Second, the four yield variables are usually highly correlated, which is accommodated through the use of multivariate modeling. Third, mortality rates present a censoring mechanism where almost half of the fed pens contain no death losses prior to slaughter. This clustering of mass at zero presents biases when traditional least squares methods are used.

This paper provides two distinct contributions to existing research. The first is to develop a continuous zero-inflated log-normal model as an alternative modeling strategy to the Tobit model

²A zero-inflated specification is used rather than other mixture specifications, such as the Hurdle model, to more accurately capture measures of cattle production yields.

and more traditional mixture models. This model will originate in a univariate case, then be extended to allow for multivariate settings. The second contribution is to more accurately describe production risk for cattle feeders by examining model performance of different regression techniques. Mortality rates play a vital role in cattle feeding profits, particularly due to the skewed nature of this variable. A clearer understanding of mortality occurrences will assist producers as well as private insurance companies, who offer mortality insurance, in managing risk in cattle operations. Additionally, production risk in cattle feeding enterprises play a significant role in profit variability, but is currently uninsured by current federal livestock insurance programs. An accurate characterization of production risk plays an important role in addressing risk for producers or insurers.

The next section develops a generalized mixture model that is specified as a zero-inflated log-normal model and is used for estimation in this research. The univariate model will precede the development of a multivariate model. The following section simulates data based on the Tobit and given zero-inflated log-normal model to evaluate the loss in efficiency from model misspecification. This evaluation will consist of how well the model fits the data and the predictive accuracy. This will lead into an application where we evaluate data from commercial cattle feedlots in Kansas and Nebraska. Results from estimation using the Tobit and zero-inflated model will be assessed using both univariate and multivariate models. The final section provides the implications of this study and avenues of future research.

The Model

In general, mixture models characterize censored dependent variables as a function of two distributions ($Y = VB$). First, B measures the likelihood of zero or positive outcomes, which have been characterized in the literature using Bernoulli and Probit model specifications. Then, the positive outcomes are independently modeled as V . A major difference between the mixture and

Tobit model is that unobservable, censored observations are not directly estimated. A generalized mixture model can be characterized as follows:

$$\begin{aligned} f(y|\theta) &= 1 - \rho(\theta) & y = 0 \\ &= \rho(\theta)g(y|\theta) & y > 0 \end{aligned} \quad (1)$$

where $\int_0^\infty g(y|\theta)dy = 1 \quad \forall \theta$. This formulation includes the standard univariate Tobit model when $\theta = (\mu, \sigma)$, $\rho(\theta) = \Phi\left(\frac{\mu}{\sigma}\right)$, and $g(y|\theta) = \frac{\phi\left(\frac{y-\mu}{\sigma}\right)}{\Phi\left(\frac{\mu}{\sigma}\right)}I(y > 0)$. Notice that in the log-normal and Gamma zero-inflated specifications to follow, ρ is modeled independently of mean and variance parameter estimates, making them more flexible than the Tobit model.

The above formulation may also be compared to a typical hurdle specification when $g(y|\theta)$ is assumed to be a zero-truncated distribution and $\rho_i(\theta)$ is represented by a Probit model. The hurdle model as specified by Cragg (1971) is not limited to the above specification. In fact, the hurdle model can be generalized to include any standard regression model that takes on positive values for $g(y|\theta)$ and any decision model for $\rho_i(\theta)$ that takes on a value between 0 and 1. In their generalized forms, both the hurdle and zero-inflated models appear to be similar, even though applications for each have differed.

Next, we develop two univariate zero-inflated models that include covariate variables, which then can be extended to allow for multivariate cases. Since only the positive outcomes are modeled through the second component, the log of the dependent variable can be taken. Taking the log of this variable works to symmetrize the dependent variable that was originally positively skewed. Using a log-normal distribution for the V random variable and allowing ρ to vary based on the conditioning variables, we can transform the basic zero-inflated model into the following form that can be generalized to include continuous distributions. We start by deriving the normal distribution to model the logarithm of the dependent variable outcomes, also known as the log-normal

distribution, of the following form

$$\begin{aligned}
 f(y_i|\beta, \alpha, \delta) &= 1 - \rho_i(\delta) && \text{for } y_i = 0 \\
 &= \rho_i(\delta) \frac{1}{y_i} \phi\left(\frac{\log(y_i) - x_i'\beta}{\sigma_i}\right) && \text{otherwise}
 \end{aligned} \tag{2}$$

where

$$\rho_i = \frac{1}{1 + \exp(x_i'\delta)} \tag{3}$$

$$\sigma_i^2 = \exp(x_i'\alpha) \tag{4}$$

which guarantees σ_i^2 to be positive and ρ_i to lie between 0 and 1 for all observations and all parameter values. Notice that this specification is nested within the generalized version in equation (1) where $g(y|\theta)$ is a log-normal distribution and $\theta = (\delta, \beta, \alpha)$.

In addition to deriving a zero-inflated log-normal distribution, we will also derive a zero-inflated Gamma distribution to demonstrate the flexibility of the zero-inflated regression models and perhaps improve upon modeling a variable that possesses positive skewness. Within a univariate framework, the sampling distribution can be easily changed by deriving V as an alternative distribution in much the same way as equation (2). Following is the specification for the zero-inflated Gamma distribution, where V is distributed as a Gamma distribution where λ_i is the shape parameter, and η_i is the rate parameter. This function can be reparameterized to include the mean of Gamma, μ , by substituting $\lambda_i = \mu_i \eta_i$, where $\eta_i = e^{(x_i'\kappa)}$ and $\mu_i = e^{(x_i'\gamma)}$. Within the Gamma distribution specification, the expected value and corresponding variance can be found to be $E(y_i) = \rho_i \mu_i$ and $Var(y_i) = \rho_i(1 - \rho_i)\mu_i^2 + \rho_i \frac{\mu_i}{\eta_i}$, respectively. Both the Gamma and log-normal univariate specifications allow for a unique set of mean and variance estimates to result from each distinct set of conditioning variables.

To model multiple dependent variables in a way that captures the covariance structure, we

utilize the relationship between joint density and conditional marginal functions. More specifically, we utilize $f(y_1, y_2) = f(y_1|y_2)f(y_2)$ to capture the bivariate relationship when evaluating y_1 and y_2 , where y_1 has a positive probability of taking on the value of 0 and y_2 is a continuous variable. In this case, $f(y_1, y_2)$ is the joint density function of y_1 and y_2 , $f(y_1|y_2)$ is the conditional probability of y_1 , given y_2 , and $f(y_2)$ is the unconditional probability of y_2 . In order to compare this model to that of the multivariate Tobit formulation, we derive a two-dimensional version of y_2 , which can easily be generalized to fit any size. However, this model restricts y_1 to be one-dimensional under its current formulation.³

We begin by parameterizing, $Z_{2i} = \log(y_2)$, which will be distributed as a multivariate normal, with mean, $X_i B^{(2)}$, and variance, Σ_{22i} . The assumption of log-normality is often made due to the ease in which a multivariate log-normal can be computed and its ability to account for skewness. This function can be expressed as $Z_{2i} \sim N(X_i B^{(2)}, \Sigma_{22i})$ where Z_{2i} is an $n \times j$ dimensional matrix of positive outcomes. This formulation allows each observation to run through this mechanism, whereas the Tobit model runs only censored observations through this mechanism.

The conditional probability of y_1 given y_2 is modeled through a zero-inflated modeling mechanism that takes into account the realizations from y_2 such that

$Y_1|Y_2 = y_2 \sim ZILN(\rho_i, \mu_i(y_2), \sigma_i^2(y_2))$ where ZILN is a zero-inflated log-normal distribution, $\mu_i(y_2)$ is the conditional mean of Z_{1i} , which is defined as $Z_{1i} = \log(y_1)$, given Z_{2i} , and $\sigma_i^2(y_2)$ is the corresponding conditional variance. More specifically,

$\mu_i(y_{2i}) = X_i B^{(1)} + \Sigma_{12i} \Sigma_{22i}^{-1} (y_{2i} - X_i B^{(2)})$ and $\sigma_i^2(y_{2i}) = \Sigma_{11i} - \Sigma_{12i} \Sigma_{22i}^{-1} \Sigma_{21i}$. This leads to the following probability density function

³This will remain an area of future research. Deriving a model that allows for multiple types of censoring may be very useful, particularly when dealing with the consumption of multiple goods. Using unconditional and conditional probabilities to characterize a more complex joint density function with multiple censored nodes would naturally extend from this modeling strategy.

$$\begin{aligned}
f(Z_{1i}|Z_{2i}) &= 1 - \rho_i(\delta) && \text{for } y_{1i} = 0 \\
&= \rho_i(\delta) \frac{1}{y_{1i}} \phi \left(\frac{Z_{1i} - \mu_i(y_{2i})}{\sqrt{\sigma_i^2(y_{2i})}} \right) && \text{for } y_{1i} > 0
\end{aligned} \tag{5}$$

Ghosh et al. (2006) demonstrate through simulation studies that similar zero-inflated models have better finite sample performance with tighter interval estimates when using Bayesian procedures instead of classical maximum likelihood methods. Due to these advantages, the previously developed models will utilize recently developed Bayesian techniques. In order to develop a Bayesian model, the sampling distribution is weighted by prior distributions. The sampling distribution, f , is fundamentally proportional to the likelihood function, L , such that $L(\theta|y_i) \propto f(y_i|\theta)$ where θ represents the estimated parameters, which for our purposes will include $\theta = (\beta, \alpha, \delta)$. While prior assumptions can have some effects in small samples, this influence is known to diminish with larger sample sizes. Additionally, prior assumptions can be uninformative in order to minimize any effects in small samples. For each parameter in the model, the following non-informative normal prior is assumed:

$$\pi(\theta) \sim N(0, \Lambda) \tag{6}$$

such that $\theta = (\beta_{kj}, \alpha_{kj}, \delta_{kc})$ and $\Lambda = (\Lambda_1, \Lambda_2, \Lambda_3)$ for $k = 1, \dots, K$, $j = 1, \dots, J$, and $c = 1, \dots, C$, where K is the number of conditioning variables or covariates, J is the number of dependent variables in the multivariate model, and C is the number of censored dependent variables.⁴ Additionally, Λ must be large enough to make the prior relatively uninformative.⁵

Given the preceding specifications of a sampling density and prior assumptions, a full Bayesian

⁴The given formulation applies to univariate versions when $J = 1$ and $C = 1$.

⁵ Λ is assumed to be 1,000 in this study, so that a normal distribution with mean 0 and variance 1,000 will be relatively flat.

model can be developed. Due to the difficulty in integrating a posterior distribution that contains many dimensions, Markov Chain Monte Carlo (MCMC) methods can be utilized to obtain samples of the posterior distribution using WinBUGS programming software.⁶ MCMC methods allow for the computation of posterior estimates of parameters through the use of Monte Carlo simulation based on Markov chains that are generated a large number of times. The draws arise from a Markov chain since each draw depends only on the last draw, which satisfies the Markov property. As the posterior density is the stationary distribution of such a chain, the samples obtained from the chain are approximately generated from the posterior distribution following a burn-in of initial draws.

Predictive values within a Bayesian framework come from the predictive distributions, which is a departure from classical theory. In the zero-inflated mixture model, predicted values will be the product of two posterior mean estimates. Posterior densities for each parameter are computed from Markov Chain Monte Carlo (MCMC) sampling procedures using WinBUGS software. MCMC methods allow us to compute posterior density functions by sampling from the joint density function that combines both the prior distributional information and the sampling distribution (likelihood function).⁷ Formally, prediction in the zero-inflated log-normal model is characterized by $\hat{y}_i = v_i b_i$ where v_i and b_i are generated from their predictive distributions. $\log(v_i)$ is from a normal distribution with mean ($\mu_i = x_i' \hat{\beta}$) and variance ($\sigma_i^2 = \exp(x_i' \hat{\alpha})$), while b_i is from a Bernoulli distribution with parameter $\rho(\hat{\delta})$. Since many draws from a Bernoulli will result in 0 and 1 outcomes, the mean will produce an estimate that lies between the two values. To allow for prediction of both zero and positive values, the median of the Bernoulli draws was used for prediction, so that observations that contained more than 50% of 1 outcomes were given a 1 value and the rest were given 0. This allows for observations to fully take on the continuous random variable if more than

⁶Chib and Greenberg (1996) provide a survey of MCMC theory as well as examples of its use in econometrics and statistics.

⁷WinBUGS will fit an appropriate sampling method to the specified model to obtain samples from the posterior distribution. Typically this implies Gibbs sampling with Metropolis-Hastings steps.

half of the time it was modeled to do so, while those that are more likely to take on zero values, as indicated by the Bernoulli outcomes, take on a zero value.

Comparison Using Simulated Data

This section will focus on simulating data in order to evaluate model efficiency for the two previously specified models. The major advantage to evaluating a simulated set of data, is that the true form of the data generation process is known prior to evaluation. This will offer key insights into what to expect when evaluating an application involving the cattle production data set to follow. Additionally, we will evaluate data that come from Tobit and mixture processes, which will help to assess the degree of losses when the wrong type of model is assumed. This will assist in identifying the type of data that the cattle production data set most closely represents. In simulating data, there will be two key characteristics that will align the simulated data set with the cattle production data set to be used in the next section. First, cattle production yield variables have been shown to possess heteroskedastic errors. To accommodate this component error terms will be simulated based on a linear relationship with the conditioning variables. While the first set of simulations will consist of homoskedastic errors, the remaining simulations will use heteroskedastic errors. Second, we are concerned with simulated data that exhibit nearly 50% censoring to emulate the cattle production data set to be used as an application in the next section.

Past research has focused on modeling agricultural yields, while research dealing specifically with censored yields is limited. The main reason for the lack of research into censored yields is because crop yields are not typically censored at upper or lower bounds. However, with the emergence of new livestock insurance products, new yield measures must be quantified in order for risks to be properly identified. In contrast to crop yield densities, yield measures for cattle health possess positive skewness, such as the mortality rate and veterinary costs. Crop yield densities typically possess a degree of negative skewness as plants are biologically limited upward by a

maximum yield, but can be negatively impacted by adverse weather, such as drought. Variables such as mortality have a lower limit of zero, but can rise quickly in times of adverse weather, such as prolonged winter storms or disease. The simulated data set used for these purposes will possess positive skewness as well as a relatively high degree of censoring, in order to align with characteristics found in cattle mortality data for cattle on feed.

First, a simplified simulated data set will be examined with a varying number of observations. We assume in this set of simulations that that errors are homoskedastic. The simulated model will be as follows

$$y_i^* = \beta_0 + \beta_1 x_{1i} + \beta_2 x_{2i} + \varepsilon_i \quad (7)$$

$$\varepsilon_i \sim N(0, \sigma^2) \quad (8)$$

$$y_i = \max(y_i^*, 0) \quad (9)$$

In this scenario, the censored and uncensored variables come from the same data generation process.⁸ For each sample size, starting seeds were set in order to replicate results. Then, values for x_i ranged from 1 to 10, based on a uniform random distribution.⁹

Error terms are distributed as a normal, centered at zero with a constant variance set to σ . y_i^* is then computed from equation (7) and all negative values are replaced with zeros, in order to simulate a censored data set. The degree of censoring in these simulated data sets ranged from 49% to 62%.

While the first set of simulations provide a basis for evaluations, the assumptions of homoskedastic errors is a simplifying assumption which has not been shown to hold in the application of cattle production yields. In order to more closely align with the given application, we now

⁸Simulated values are based on $(\beta_0, \beta_1, \beta_2) = (2.0, 3.7, -4.0)$ and $\sigma^2 = 1$.

⁹Values for x_i might also be simulated using a normal distribution. A uniform distribution will more evenly spread values of x_i from the endpoints, while a normal distribution would cluster the values near a mean, without endpoints (unless specified). Additionally, a uniform distribution will tend to result in fatter tails in the dependent variable due to the relatively high proportion of extreme values for x_i .

move to simulate a data set containing heteroskedastic errors. Heteroskedasticity is introduced into this data by constructing ε_i by substituting equation (10) for equation (8) and accounting for the relationship between the error terms and the conditioning variables such that

$$\varepsilon_i \sim N(0, \sigma_i^2) \quad (10)$$

where $\sigma_i^2 = \exp(\alpha_0 + \alpha_1 x_{1i} + \alpha_2 x_{2i})$.¹⁰ These equations impose a dependence structure on the error term, where the variance is a function of the conditioning variables. This specification has been shown to better characterize cattle production yield measures (Belasco et al., 2006). Simulations were conducted in much the same manner as the previous set of simulations, with the addition of heteroskedastic errors.

Two thirds of this simulated data set is used for estimation, while the final third is used for prediction. This allows us to test both model fit measures as well as predictive power. In this study, Tobit regressions use classical maximum likelihood estimation techniques, while zero-inflated models use Bayesian estimation techniques. To derive measures of model fit we use the classical computation of Akaike's Information Criteria (AIC) (Akaike, 1974) and derive a similar measure for Bayesian analysis, the Deviance Information criteria (DIC) (Spiegelhalter et al., 2002). DIC results are interpreted similar to AIC in that smaller values of the statistics reflect a better fit. A major difference is that AIC is computed based on the optimized value of the likelihood function where $AIC = -2\log L(\hat{\beta}, \hat{\alpha}) + 2P$. In this case, P is the dimension of θ , which is 3 in the case of homoskedastic errors and 6 with heteroskedastic errors. Alternatively, DIC is constructed by including prior information and is based on the deviance at the posterior means of the estimated parameters. A penalization factor for the number of parameters estimated is also incorporated into this measure. The formulation for DIC can be written as $DIC = \bar{D} + p_D$ where p_D is the effective number of parameters and \bar{D} is a measure of fit that is based on the posterior expectation of

¹⁰Simulated values are based on $(\alpha_0, \alpha_1, \alpha_2) = (-1.5, 0.8, -0.6)$.

deviance. These measures are specified as $\bar{D} = E[-2\log L(\delta, \beta, \alpha)|y]$ and $p_D = \bar{D} + 2\log L(\tilde{\delta}, \tilde{\beta}, \tilde{\alpha})$, which takes into account the posterior means, $\tilde{\delta}$, $\tilde{\beta}$, and $\tilde{\alpha}$.

Robert (2001) reports that DIC and AIC are equivalent when the posterior distributions are approximately normal.¹¹ Spiegelhalter et al. (2003) warns that DIC may not be a viable option for model fit tests when posterior distributions possess extreme skewness or bimodality. These concerns do not appear to be problematic in this study.

To measure the predictive power within a modeling strategy, we compute the Mean Squared Prediction Error (MSPE) associated with the final third of each simulated data set. MSPE allows us to test out of sample observations to assess how well the model predicts dependent variable values. MSPE is formulated as $MSPE = \frac{1}{m} \sum_{i=1}^m (\hat{y}_i - y_i)^2$ where m is some proportion of the full data sample, such that $m = \frac{n}{b}$. For our purposes, $b = 3$, which allows for prediction on the final third, based on estimates from the first two thirds. This allows for a sufficient amount of observations available for estimation and prediction.

We estimate the simulated data set, given the above specifications, with the three models that have previously been formulated. MCMC sampling is used for Bayesian estimation with a burn-in of 1,000 observations and three Markov chains. WinBUGS uses different sampling methods, based on the form of the target distribution. For example, the zero-inflated Gamma distribution uses Metropolis sampling that fine tunes some optimization parameters for the first 4,000 iterations, which are not counted in summary statistics.

Results from Tobit regressions on the simulated data set with homoskedastic and heteroskedastic errors can be found in Table 1. Based on AIC/DIC criteria, the zero-inflated log-normal regression model outperforms the Tobit model at all data sample levels. This is particularly interesting given the fact that simulation was based on a Tobit model. In cases where the degree of censoring is high, the parameter estimates that estimate the likelihood of censoring add more precision to the model. This impact is likely to diminish as the degree of censoring decreases and increases for

¹¹The normality of all parameter estimates is supported by the posterior plots supplied by WinBUGS.

higher degrees of censoring.

The poor performance of the Gamma distribution highlights the problem associated with assuming an incorrect distribution. The Gamma distribution does particularly well with positive skewness, however, the degree of skewness in this model is not sufficient to overcome the incorrect distributional assumption.

Lower MSPE indicates that the prediction of the out of sample portion of the data set favors that of the Tobit model at all sample levels. MSPE penalizes observations with large residuals that tend to be more prevalent as the dependent variable value increases. Gurmu and Trivedi (1996) point out that mixture models tend to overfit data. By overfitting the data, model fit tests might improve, while prediction remains less accurate. This might explain part of the reason that mixture models appear to fit this particular set of simulated data better, while lacking prediction precision. Both zero-inflated models had particular trouble when predicting higher values of y , resulting in high MSPE values. The wide spread of MSPE values is largely a result of simulating data that contains a high level of variability and a relatively small number of observations.

It is also important to point out that the Tobit model assumes positive observations are distributed by a truncated normal distribution, while log-normal and Gamma distributions also take on only positive values but look very different than the truncated normal distribution. With roughly half of the sample censored, the density function from a truncated normal density would likely predict a larger mass near the origin, while the log-normal and Gamma distributions carry fatter tails.

As previously mentioned, another major difference between the hurdle and zero-inflated models in practice is the difference in modeling the binary decision variable using Probit and Bernoulli distributions, respectively. Based on the simulated data, the binary variables were computed using both methods did not appear to be significantly different.

As an alternative to the preceding simulation process, data can also be simulated using two separate data processes that emulate that of a mixture model more consistent with zero-inflated

models. The major distinction between this simulation and the previously developed Tobit-based data set, is that the probability of a censored outcome is modeled based on equation (3). Additionally, outcomes that are described by a probability density function must be positive, which is achieved by taking the exponential of a normal distribution.¹²

Results from the second simulation can be found in Table 2. Once again, the results indicate a superior model fit with the zero-inflated model, relative to the Tobit model. Additionally, the zero-inflated models possess a substantially lower MSPE, indicating better out of sample prediction performance. Both zero-inflated formulations are capable of accounting for positive skewness. For the larger sample sizes, the Gamma formulation shows superior prediction ability, while the log-normal formulation is a better fit with the data. These results may come from the data generating process where the positive observations are generated from a log-normal distribution, however, the Gamma formulation predicts the outcomes that may come furthest from zero most accurately.

Accounting for both types of data generating processes, zero-inflated models are better able to fit data that contain a high degree of censoring. Prediction appears to depend on the data generation process. If the data comes from a zero-inflated model, then prediction is more efficient when it is from a zero-inflated model. Alternatively, if all data comes from the same data generating process, then the Tobit may predict better than the proposed alternatives. One notable feature of the results generated from this simulation is that values for DIC appear to take on both positive and negative values. As mentioned previously, lower DIC/AIC indicate better fit measures. Therefore, a negative DIC is favorable to a positive AIC, which is the case under this scenario.

Most current research concerning censored data is focused on multivariate systems of equations. This is because of the many applications that make use of multivariate relationships in

¹²This is the same as assuming y_i is distributed as a log-normal distribution. Alternatively, data could be generated using a truncated normal distribution where simulations on a normal continues until all values are positive through iterations that spit out negative values and keep only positive values. The two methods would generate two very different data sets. Simulated values are based on values $(\beta_0, \beta_1, \beta_2) = (0.2, 0.4, -0.6)$ and $(\delta_0, \delta_1, \delta_2) = (-4.0, -5.0, 7.0)$. Additionally $\sigma^2 = 1$ and $(\alpha_0, \alpha_1, \alpha_2) = (-0.2, 0.1, -0.6)$ refer to homoskedastic and heteroskedastic simulations, respectively.

current studies. For this reason, it will be important to simulate a multivariate data set that comes from both a Tobit and a two-step process. Since multivariate data comes in both forms, it will be important to evaluate each to see the potential bias from assuming, for example, that data are generated from a multivariate Tobit model when a two-step process is more appropriate. The Tobit process is constructed from a multivariate normal distribution that assumes a specified covariance matrix. Censoring in this case occurs when the censored dependent variable falls below a specified level.¹³ Alternatively, the two-step process uses a Bernoulli distribution to estimate the likelihood of a censored outcome, which is also a function of the conditioning variables.¹⁴ To be consistent, the same variables that increase the likelihood of a censored outcome in the two-step case, also decrease the mean of the variable so that they increase the likelihood of a variable being censored in the Tobit process. Y_1 and Y_2 are variables without censoring, while Y_3 contains censoring in nearly half of its observations.

The results from a simulated data set based on a multivariate Tobit model are shown in Table 3. Overall, the fit of both models appear to be more closely aligned with the Tobit model in the first two simulations, while the zero-inflated model more accurately fits the model with the largest sample size. Additionally, the Tobit model predicts more efficiently, as shown by the lower MSPE in most cases. This is consistent with the univariate results and again is not surprising, given the data were generated from a Tobit model.

It is surprising the closeness of model fit, when we compare the results from data simulated from a mixture model, as shown in Table 3. Here, the zero-inflated model strongly improves the model fit, relative to the Tobit formulation. It is surprising that while most MSPE measures are close, they tend to favor the Tobit model formulation.

These simulations were conducted to compare the efficiency of the two given models in

¹³This method essentially simulates a system of equations that includes the latent variable, where the latent variable is unobservable to the researcher. Simulated values were based on $\beta = (5, 4, -1; 5, 5, -1; 1, 2, -2)$, $\alpha = (-1.5, 0.5, -1; 0.4, 0.5, -1; -3, .5, -1)$, and cross products $(t_{12}, t_{13}, t_{23})=(0.6, -0.4, 0.3)$.

¹⁴Values for the simulation based on a multivariate mixture model were based on Tobit parameters with the addition of $\delta = (-4.0, -1.8, 3.0)$.

cases where the data are generated from a single data generating process, and that of a two-step process. Simulation results indicate that both models do relatively well in fitting the data, when the data come from a Tobit model. Alternatively, the model fit tests quickly move in the direction of the zero-inflated model in cases where the data comes from a mixture model and the non-zero observations are modeled using a multivariate log-normal distribution. Prediction of out of sample observations appear to be more efficiently characterized through the Tobit model. This is interesting given the fact that classical Tobit prediction uses only the optimized parameter values, while the zero-inflated model employs a Bayesian method that employs the entire posterior distribution of the estimated parameter values. Overall, the ZILN model tends to fit the data particularly well whether the data are generated from a Tobit or two-step process. This may result from the additional parameters that characterize the probability of a non-zero outcome in mixture models. However, this over-fitting does not assist in improving prediction, as prediction tends to be more precise when the appropriate model is specified.

This section has offered some initial guidance into evaluating real data through the use of simulated data sets. The simulated data sets offer the opportunity to evaluate the performance of the Tobit and zero-inflated models in situations where the true data generation process is known. The next section will look to evaluate the same postulated models in an application where the true data generating process is unknown.

An Application

This section applies the preceding models to cattle production risk variables. The data set that will be used possesses many of the same properties from the last section, such as a relatively high degree of censoring and positive skewness in the dependent variables. The proposed zero-inflated log-normal model is hypothesized to characterize censored cattle mortality rates better than the Tobit model because of the two part process that mortality observations are hypothesized

to follow, as well as based on a visual inspection of positive mortality observations being more closely characterized by a log-normal distribution. Cattle mortality rates are thought to follow a two step process because pens tend to come from the same, or nearby, producers and are relatively homogenous. Therefore, a single mortality can be seen as a sign that a pen that is more prone to sickness or disease. Additionally, airborne illnesses are contagious and can be spread rather quickly throughout the pen. Other variables that describe cattle production performance are introduced and evaluated using the previously developed multivariate framework. These variables include DMFC, which is measured as the average pounds of feed a pen of cattle require to add a pound of weight gain, and ADG, which is the average daily weight gain per head of cattle. VCPH is the amount of veterinary costs per head that are incurred over the feedlot stay.

This research focuses on the estimation and prediction of cattle production yield measures. Cattle mortality rates from commercial feedlots are of particular interest due to their importance in cattle feeding profits. Typically, mortality rates are zero or small, but can rise significantly during adverse weather, illness, or disease. The data used in this study consists of 5 commercial feedlots residing in Kansas and Nebraska, and includes entry and exit characteristics of 11,397 pens of cattle at these feedlots. Table 4 presents a summary of characteristics for different levels of mortality rates, including no mortalities

Particular attention will be placed on whether zero or positive mortality rates can be strongly determined based on the data at hand. The degree of censoring in this sample is 46%, implying that almost half of the observations contain no mortality losses. There is strong evidence that mortality rates are related to the previously mentioned conditioning variables, but we will need to determine whether censored mortality observations are systematically different than observed positive values. Positive mortality rates may be a sign of poor genetics coming from a particular breeder or sickness picked up within the herd. The idea here is that the cattle within the pen are quite homogeneous. Homogeneity within the herd is desirable as it allows for easier transport, uniform feeding rations, medical attention, and the amount of time on feed. If homogeneity within the herd holds, then pens

that have mortalities can be put into a class that is separate from those with no mortalities.

However, mortalities also may occur without warning and for unknown reasons. Glock and DeGroot (1998) report that 40% of all cattle mortalities in a Nebraska feedlot study were directly caused by Sudden Death Syndrome.¹⁵ However, the authors also point out that these deaths were without warning, which could be due to a “sudden death” or lack of observation by the feedlot workers. Smith (1998) also reports that respiratory disease and digestive disorders are responsible for approximately 44.1% and 25.0% of all mortalities, respectively. The high degree of correlation between dependent variables certainly indicates that lower mortality rates can be associated with different performance in the pen. However, the question in this study will be whether positive mortality rates significantly alter the performance. For this reason, we estimate additional parameters to examine the likelihood of a positive mortality outcome in the zero-inflated regression model.

A recent study by Belasco et al. (2006) found that the mean and variance of mortality rates in cattle feedlots are influenced by entry-level characteristics such as location of the feedlot, placement weight, season of placement and gender. These variables will be used as conditioning variables. By taking these factors into account, variations will stem from events that occur during the feeding period as well as characteristics that are unobservable in the data. The influence of these parameters will be estimated using the previously formulated models, based on two-thirds of the randomly selected data set where $n = 7,598$. The remaining portion of the data set, $m = 3,799$, will be used to test out of sample prediction accuracy. Predictive accuracy is important in existing crop insurance programs where past performance is used to derive predictive density functions for current contracts.¹⁶

After estimating expected mortality rates, based on pen-level characteristics, we will focus

¹⁵Glock and DeGroot (1998) loosely define Sudden Death as any case where feedlot cattle are found dead unexpectedly.

¹⁶The most direct example of this is the Average Production History (APH) crop insurance program that insures future crop yields that are based on a 16-year average of production history.

our attention to estimating mortality rates as part of a system of equations that includes other performance and health measures for fed cattle, such as dry matter feed conversion (DMFC), average daily gain (ADG), and veterinary costs (VCPH), which are additional measures of cattle production yields.

Estimation Results

A desirable model specification will be one that fits the data in estimation and is able to predict dependent variable values with accuracy. For these reasons, these models will be compared in a way similar to the simulated data sets. First, we begin with univariate results. Results from using a classical Tobit model with heteroskedastic errors to model cattle mortality rates can be found in Table 5.

Tobit estimates for β measure the marginal impact of changes in the conditional variables on the latent mortality rate.¹⁷ For example, the coefficient corresponding to in-weight, states that a 10% increase in entry weight lowers the latent variable by 3.9%.¹⁸ The estimates for α measure the relative impact on the variance. For example, the estimation coefficient corresponding to fall implies that a pen placed in that period is associated with a variance that is 32% higher than the base months containing summer. MSPE is computed as the average squared difference between the predicted and actual mortality rates.

Next, we move to estimate the same set of data using the previously developed zero-inflated models in order to test our hypothesis that they will have a better fit. Before proceeding to estimation, there are a few notable differences when using classical and Bayesian methods. First,

¹⁷The Tobit specification assumes that the latent variable is a continuous, normally distributed variable that is observed for positive values and zero for negative values. Marginal changes in the latent variable must then be converted to the marginal changes in the observed variable, in order to offer inferences on the observable variable. The marginal impact on mortality rates can be approximated by multiplying the marginal impact on the latent variable by the degree of censoring (Greene, 1981)

¹⁸McDonald and Moffitt (1980) show how Tobit parameter estimates can be decomposed into two parts, where the first part contains the effect on the probability that the variable is above zero, while the second part contains the mean effect, conditional on being greater than zero.

Bayesian point estimates are typically computed as the mean from Monte Carlo simulations of the posterior density function. This estimation process is done in two parts; first the likelihood of a zero value is modeled, followed by simulating the positive predicted realizations, based on a log-normal distribution. In addition to the mean value, additional characteristics of the posterior distributions are supplied, such as the median, 2.5 and 97.5 percentile values, and the standard deviation, as well as the Monte Carlo standard error of the mean. Results from the zero-inflated log-normal model are shown below in Table 6.

Parameter estimates in the zero-inflated model refer to two distinct processes. The first process includes the likelihood of a zero outcome or one described by a log-normal distribution. This process is estimated through δ utilizing equation (3). Based on this formulation, the parameter estimates can be expressed as the negative of the marginal impact of the conditional variable on the probability of a positive outcome, relative to the variance of the Bernoulli component:

$$\delta_k = -\frac{\partial \rho_i}{\partial x_{ki}} \cdot \frac{1}{\rho_i} \cdot \left[\frac{1 + \exp(x'_i \delta)}{\exp(x'_i \delta)} \right] = -\frac{\partial \rho_i}{\partial x_{ki}} \cdot \frac{1}{\rho_i(1 - \rho_i)} \quad (11)$$

where the variance is shown as $\rho_i(1 - \rho_i)$. For example, entry weight largely and negatively influences the likelihood of positive mortality rates. This is not surprising given that more mature pens are better equipped to survive adverse conditions, whereas younger pens tend to be more likely to result in mortalities. Alternatively, mixed pens have a negative δ coefficient which implies that there is a positive relationship, relative to heifer pens. Therefore, if a pen is mixed, it has a higher probability of incurring positive mortality realizations that can be modeled with a log-normal distribution.

The Tobit model assumes that estimates for β and δ will work in the same way. For most variables, δ coefficients are negatively related to β coefficients, which points to directional consistency. For example, increases to entry weight shift the mean of mortality rates downward and also decrease the probability of a positive outcome. This does not necessarily mean that the two

processes work identically, as is assumed with the Tobit model, but rather tend to generally work in the same direction.

Parameter estimates for β refer to the marginal impact that the conditioning variables have on the positive realizations of mortality rates. Interpretations for these parameters refer to the marginal increase in the log of mortality rate. For example, an increase in entry weight by 1.0% is associated with a reduction in mortality rates by 0.9% for the observations that experience a positive mortality rate.

It is interesting to note the different implications from parameter estimates from the Tobit and ZILN models. For example, an insignificant mean parameter estimate for the variable KS in the Tobit model implies that mortality rates are not significantly impacted by feedlot location. However, parameter estimates from the ZILN model infer that pens placed into feedlots located in Kansas have a lower likelihood of a positive mortality realization by 13.7%, relative to Nebraska feedlots. At the same time, pens placed in Kansas that have a positive mortality rate, can be expected to realize a rate that is 11.8% higher than Nebraska feedlots. This might seem strange to have significant impacts in opposite directions that influence both the likelihood of a mortality and the positive mortality rate, but by distinguishing between these processes we can isolate their respective impacts. One possible explanation might be that Kansas lots spend more time to prevent mortalities from occurring through vaccinations or backgrounding, but are not able to prevent the spread of disease as quickly as the Nebraska feedlots. This is a notable departure from the Tobit model which saw no significant influence since these impacts essentially canceled each other out.

Another notable difference is in seasonal impacts on the mean of mortality rates. While the none of the seasonal variables are significantly different than summer under the Tobit model, both Fall and Spring are significantly different under the ZILN specification. The ZILN results are more inline with expectations as Fall placement are put under stress from extremely cold weather, which is different from summer placements. In fact, most of the pens with mortality losses above 10% in this data sample come from pens placed in the fall months.

The zero-inflated log-normal models also demonstrate a superior ability to characterize and predict cattle feedlot observations. A DIC measure of 18,742.3 demonstrates a closer fit, relative to the Tobit model, which has an AIC value of 22,790.7. Additionally, MSPE is minimized when using the ZILN model. The likely explanation for these findings is due to the data generating process. Cattle mortalities appear to be part of a two part process where once a pen experiences a mortality, the rate of mortalities can be modeled using a distinct distribution from those observations without mortalities.¹⁹

The given data set was also modeled using a zero-inflated Gamma (ZIG) distribution. While the Bernoulli component is similar to the ZILN model, this model characterizes the positive observations using a Gamma distribution, which also can take into account highly skewed data. The results from the ZIG model are shown below in Table 7.

Regressions from univariate mortality models offer information concerning the relative impacts each conditioning variable has on mortality rates. However, this variable is likely better characterized in a multivariate setting with other variables that explain the health and performance of cattle on feedlots, ultimately describing production risk in cattle feeding enterprises. To this end, the multivariate Tobit model and multivariate zero-inflated models were used to characterize these four variables, described earlier. The results from the multivariate Tobit model are shown in table 8.

Results from this estimation mostly appear to be in line with the estimation from Belasco et al. (2006), as well as the first essay. While the same data set was used, this study employs two-thirds of the data for estimation and the final third for out of sample prediction. Mortality rates contain the most variability in prediction, mostly due to the relative lack of explanatory power from

¹⁹This method may also be useful in situations where the data have some similar characteristics. Examples may be modeling the prevalence of animal disease, where a Bernoulli distribution characterizes the likelihood of an outbreak. Once an outbreak has occurred, a model describing its biological spread is needed. This strategy may also extend into areas of bio-security and food safety issues where biological processes may be allowed to spread within a population once contamination has occurred. Additionally, data that are characterized with a high degree of censoring can be efficiently characterized through the use of a zero-inflated model, as shown in earlier simulations.

the conditioning variables. While these *ex-ante* variables offer information on expected mortality rates, there does still appear to be a bit more unexplained variation than with the other variables. Performance variables, such as DMFC and ADG, are largely determined by observable biological traits. While not all of these biological traits are captured in these data, there does not appear to be a large portion unexplained by these variables.

The elements contained within the covariance matrix are under the estimates labeled as 'Heteroskedasticity'.²⁰ The sign of the off-diagonal covariance elements describe the relationship between two variables. For example, DMFC and ADG are negatively related with a coefficient of -4.09, since a healthy pen of cattle will be expected to have a low feed conversion rate and a high rate of gain. Additionally, MSPE is broken out by dependent variable. MORT has the highest MSPE, which illustrates the lack of predictive power with that variable.

Next, the multivariate zero-inflated model is applied to the cattle feedlot data set and results are shown in Table 9. Estimates displayed here are consolidated, relative to the univariate table due to space constraints. In a Bayesian framework, confidence intervals are typically computed using the highest posterior density region, which will be different from a classical confidence interval when posterior distributions are bi-modal or asymmetric. Since the posterior estimates do not show bi-modal attributes, we proceed by taking the interval between the 2.5 and 97.5 percentiles to test whether the variable is significantly different from zero. While this is a departure from Bayesian theory, it nearly aligns with significance tests for the multivariate Tobit model. For example, in the zero-inflated model, if the posterior density function does not cross zero in the given interval, which includes 95 percent of the posterior density, then it is said to be significant at the 5% level.

Many of the same estimates appear in the zero-inflated table, with the addition of 'Delta' terms, which describe the negative of the relative impact on the probability of a non-zero outcome. These estimates are computed in the same way as the univariate version of this model, leading to

²⁰Belasco et al. (2007) provide a more detailed discussion concerning the construction of the covariance matrix for the Tobit model.

many of the same inferences. Additionally, parameter estimates corresponding to DMFC, ADG, and VCPH are mostly the same between the Tobit model and ZILN models. Parameter estimates corresponding to MORT are different between the two models, as discussed with the univariate model.

The zero-inflated model does a superior job of fitting the data and in terms of prediction accuracy, relative to the Tobit model. DIC for the ZILN model is substantially lower than AIC in the Tobit model, mainly due to the more accurate fit for Mortality rates, which contributes quite a lot of unexplained variability to the system of equations. The more efficient modeling of mortality rates stem from the ability of the zero-inflated model to more accurately represent MORT by taking into account the two part process inherent in mortality rates. MSPE measures are approximately the same for each of the non-censored variables, largely because they are modeled in a similar fashion. However, more information about mortality rates in the zero-inflated model add to more accurately model the other variables. In fact, the multivariate zero-inflated model predicts every dependent variable with more precision, leading to large gains in both prediction and model fitting.

We can decompose the total DIC and LL values from the multivariate zero-inflated model into dependent variable components, which is shown in Table 10.²¹ This table is helpful in breaking down model fit measures to identify the performance of the model on each variable. MORT is more accurately characterized in a multivariate setting because of the effects from other non-censored variables. Recall, that the expected value and variance of MORT accounts for the uncensored variable levels in the multivariate setting. D represents the estimation on the parameters of 'Delta', which performs roughly similar in both multivariate and univariate situations, since it uses the same modeling mechanism in each case. DMFC is modeled very tightly, as shown by the negative DIC, while ADG and VCPH leave some variability unestimated. The results from the total line are reported with the full model results in Table 9.

²¹LL values are computed by dividing Dhat by -2, since $Dhat = -2 * LL(\hat{\beta}, \hat{\gamma}, \hat{\delta})$. This aligns with LL values in the Tobit model which are computed based on optimized values. Along the same lines, Dhat is computed by using the optimal posterior means.

Implications and Recommendations

Modeling censored data remains a large area of concern and current research in econometrics. While use of the Tobit model may be well-justified in certain instances, the results from both simulated and actual cattle feeder data sets suggest the use of a zero-inflated modeling mechanism. This is particularly true in instances where data come from a two-step process. While two-step processes have been applied to hurdle models, zero-inflated models have largely been ignored in economic studies. This is mainly a result of the past limitation of zero-inflated models to count data. In this study, a mixture model is developed that can handle both univariate and multivariate situations rather efficiently, in addition to nesting the standard Tobit model. Additionally, the inherent parametric flexibility allows for distributional assumptions to change based on the data on hand, rather than strictly using truncated or normally distributions. Here we use a log-normal distribution to capture the positively skewed nature of cattle feedlot mortality rates, which gives the zero-inflated log-normal model significant advantages over the Tobit model. Advantages in model fit for the ZILN model stem from the ability to isolate and identify the impacts from observing a positive mortality rate and the level of mortality rates. However, the Tobit model is also shown to be a special case of the general mixture model.

Production risk in cattle feeding enterprises is inherently complex, given the many areas risk can originate. Results from this research demonstrate the potential gains from using this particular mixture model. Before applying this model to the data, simulations were conducted to test the model's ability to predict and fit data generated in different forms. These simulations provide results that support the use of the mixture model, in both prediction and model fit, when the data is from a two-step process. Additionally, the mixture model demonstrated a strong ability to fit the data, even when the data are generated based on a Tobit model. These results are in general agreement with the results obtained within our application of cattle feeding.

A solid understanding of cattle production risks is limited by our ability to characterize vari-

ability. The proposed model takes a step forward in developing a modeling strategy that can be used to measure other livestock or live animal productive measures. By more accurately characterizing these risks insurance companies, animal producers, and operators can better understand the risks involved with animal production. Future research is currently focusing on developing this model to account for systems where censoring occurs in more than three variables, which is currently problematic in classical estimation techniques. Examples where this particular model might be useful include consumption, livestock disease spread, or production processes.

Additionally, the flexibility of this model allows for uses outside of live animal yields. The major flexibility in the proposed model lies in the ability to make different distributional assumptions. Distributional assumptions typically need to be made in cases when data cannot fully explain variability. However, nonparametric and semi-parametric methods may be of particular interest when large data sets are evaluated, since they allow empirical data to create a unique density. With more data available on live animal yields, augmenting this model to include these types of density functions may provide additional precision.

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Table 1: Simulation results based on Tobit model

n	Model	MSPE	LL	AIC/DIC
Homoskedastic errors				
200	Tobit	0.773	-86.044	184.088
	ZILN	23.982	-58.162	122.934
	ZIG	4.453	-165.280	337.138
500	Tobit	0.460	-258.590	529.179
	ZILN	96.064	-170.905	350.238
	ZIG	52.720	-497.998	1,002.490
1,000	Tobit	0.466	-508.902	1,029.805
	ZILN	94.809	-400.526	809.331
	ZIG	47.098	-985.960	1,977.590
Heteroskedastic errors				
200	Tobit	16.624	-87.057	186.114
	ZILN	20.416	-57.162	123.416
	ZIG	17.083	-187.151	381.949
500	Tobit	6.205	-248.387	508.774
	ZILN	10.156	-168.842	348.661
	ZIG	12.018	-546.32	1,100.390
1,000	Tobit	10.012	-453.739	919.478
	ZILN	14.528	-358.822	728.513
	ZIG	16.745	-1,024.810	2,058.140

Table 2: Simulation results based on mixture model

n	Model	MSPE	LL	AIC/DIC
Homoskedastic errors				
200	Tobit	1.953	-95.535	203.069
	ZILN	0.280	-2.583	11.510
	ZIG	0.303	6.905	-7.865
500	Tobit	2.153	-276.410	564.821
	ZILN	0.079	29.148	-50.412
	ZIG	0.083	13.379	-20.674
1,000	Tobit	1.189	-499.676	1,011.351
	ZILN	0.044	21.211	-33.565
	ZIG	0.046	82.563	-158.735
Heteroskedastic errors				
200	Tobit	77.813	-40.024	92.049
	ZILN	63.386	-26.204	60.732
	ZIG	64.052	-76.506	160.651
500	Tobit	12.941	-130.961	273.923
	ZILN	4.303	-102.802	214.994
	ZIG	3.971	-235.094	478.824
1,000	Tobit	4.610	-272.204	556.407
	ZILN	2.948	-183.034	376.549
	ZIG	2.468	-430.032	867.893

Table 3: Multivariate simulation results

n	Model	Y_1 MSPE	Y_2 MSPE	Y_3 MSPE	LL	AIC/DIC
Based on Tobit model						
200	Tobit	0.481	1.281	0.290	-168.227	378.454
	ZILN	0.482	3.236	3.165	-156.399	354.223
500	Tobit	0.328	0.789	0.312	-477.028	996.056
	ZILN	0.327	2.182	5.057	-499.801	1,043.380
1,000	Tobit	0.261	0.639	0.205	-912.345	1,866.691
	ZILN	0.261	1.211	3.167	-907.265	1,859.090
Based on mixture model						
200	Tobit	0.343	0.995	1.032	-197.166	436.332
	ZILN	0.355	1.817	1.950	-107.884	243.534
500	Tobit	0.376	0.858	2.395	-2,636.920	5,315.839
	ZILN	0.373	3.713	3.205	-347.296	739.812
1,000	Tobit	0.220	1.067	2.760	-4,599.517	9,241.034
	ZILN	0.226	1.714	5.169	-585.280	1,216.920

Table 4: Comparison of pens with differing mortality losses

Variable	Mortality Rate (%) ^a					
	0	0.01 - 1	1 - 2	2 - 3	3 - 4	>4
Observations	5,161	2,415	2,327	744	305	445
DMFC	6.05	6.27	6.21	6.34	6.42	6.85
ADG	3.49	3.35	3.28	3.11	3.06	2.82
Intake	20.96	20.82	20.15	19.52	19.49	18.88
VCPH	10.18	10.08	12.46	15.67	17.89	26.57
InWt	754.27	751.53	719.72	686.35	699.00	671.63
OutWt	1,188.72	1,179.90	1,168.75	1,152.95	1,158.40	1,144.66
HeadIn	120.24	182.04	126.19	123.14	114.72	110.57
Days on Feed	123.45	125.66	133.44	143.83	141.57	150.57
Proportion of sample:						
Winter	0.24	0.27	0.26	0.29	0.29	0.21
Spring	0.26	0.24	0.21	0.16	0.17	0.10
Summer	0.27	0.26	0.26	0.25	0.24	0.30
Fall	0.23	0.23	0.27	0.30	0.30	0.39
Steers	0.53	0.56	0.49	0.43	0.42	0.35
Heifers	0.36	0.37	0.37	0.36	0.38	0.33
Mixed	0.10	0.07	0.14	0.20	0.20	0.32
KS	0.82	0.76	0.82	0.77	0.79	0.82

^aNote: A mortality rate that results in a whole number is placed into the higher bins (ie, 3.00% is placed in 3-4 bin)

Table 5: Univariate Tobit estimates of fed cattle mortality parameters

Variables	$\beta^{\#}$		$\alpha^{\textcircled{a}}$	
	coeff.	se.	coeff.	se
Intercept:	25.782*	1.515	12.068*	1.114
Steers:	0.168*	0.055	-0.021	0.048
Mixed:	0.307*	0.124	0.984*	0.073
Kansas:	-0.068	0.058	0.292*	0.058
log(inwt):	-3.893*	0.231	-1.654*	0.172
Winter:	0.065	0.068	-0.243*	0.061
Fall:	0.043	0.079	0.315*	0.061
Spring:	-0.089	0.069	-0.278*	0.065
LL:	-11,389.353			
AIC:	22,790.706			
MSPE:	2.661			

*Denotes estimate is significant at the 0.05 level

$\beta^{\#}$ measures the marginal change on the mean of the latent variable

$\alpha^{\textcircled{a}}$ measures the relative impact on the variance

Table 6: Univariate ZILN estimates of fed cattle parameters

node	mean	sd	MC error	2.5%	median	97.5%	Parameter
Intercept	6.047	2.193	0.160	0.334	6.466	9.076	$\beta^{\#}$
Steers	0.011	0.034	0.002	-0.066	0.014	0.070	
Mixed	0.394	0.037	0.001	0.321	0.394	0.467	
KS	0.118	0.028	0.001	0.062	0.119	0.172	
log(inwt)	-0.907	0.336	0.025	-1.371	-0.970	-0.033	
Winter	-0.020	0.030	0.001	-0.078	-0.021	0.038	
Fall	0.087	0.032	0.001	0.025	0.086	0.151	
Spring	-0.085	0.031	0.001	-0.148	-0.085	-0.023	
Intercept	-3.379	1.240	0.090	-5.008	-3.695	0.324	
Steers	0.059	0.051	0.002	-0.043	0.059	0.157	
Mixed	-0.274	0.072	0.001	-0.414	-0.273	-0.133	
KS	0.078	0.060	0.002	-0.034	0.078	0.199	
log(inwt)	0.618	0.191	0.014	0.049	0.666	0.877	
Winter	0.163	0.061	0.001	0.046	0.163	0.280	
Fall	-0.069	0.06	0.001	-0.190	-0.069	0.048	
Spring	0.229	0.065	0.001	0.100	0.229	0.357	
Intercept	-11.380	3.070	0.224	-16.160	-11.610	-4.508	$\delta^{\textcircled{!}}$
Steers	-0.007	0.063	0.003	-0.127	-0.007	0.118	
Mixed	-0.177	0.079	0.001	-0.331	-0.177	-0.023	
KS	0.137	0.062	0.002	0.016	0.138	0.257	
log(inwt)	1.686	0.469	0.034	0.639	1.720	2.419	
Winter	-0.066	0.065	0.001	-0.196	-0.066	0.060	
Fall	-0.104	0.067	0.002	-0.237	-0.103	0.027	
Spring	0.169	0.068	0.001	0.036	0.169	0.302	
LL:	-9,341.500						
DIC:	18,742.300						
MSPE:	2.399						

$\#$ β measures the marginal change on the mean of the latent variable

\textcircled{a} α measures the relative impact on the variance

$\textcircled{!}$ δ measures the negative relative impact in the probability of a non-zero entry

Table 7: Univariate ZIG estimates of fed cattle parameters

node	mean	sd	MC error	2.5%	median	97.5%	Parameter
Intercept	2.569	0.424	0.031	1.904	2.510	3.350	γ
Steers	-0.054	0.033	0.002	-0.115	-0.054	0.010	
Mixed	0.379	0.044	0.002	0.295	0.379	0.466	
KS	0.014	0.034	0.002	-0.054	0.015	0.079	
log(inwt)	-0.410	0.066	0.005	-0.533	-0.402	-0.310	
Winter	0.035	0.040	0.002	-0.040	0.034	0.118	
Fall	0.134	0.040	0.002	0.057	0.133	0.217	
Spring	-0.188	0.044	0.002	-0.270	-0.190	-0.094	
	1.187	0.028	0.001	1.134	1.187	1.243	
Intercept	-0.465	0.427	0.031	-1.426	-0.429	0.318	δ
Steers	0.114	0.052	0.003	0.010	0.113	0.221	
Mixed	-0.168	0.078	0.003	-0.322	-0.166	-0.019	
KS	0.167	0.055	0.003	0.063	0.165	0.280	
log(inwt)	0.020	0.063	0.005	-0.102	0.015	0.156	
Winter	-0.108	0.064	0.003	-0.240	-0.106	0.013	
Fall	-0.145	0.065	0.003	-0.280	-0.145	-0.018	
Spring	0.212	0.063	0.003	0.074	0.215	0.330	
LL:	-10,985.850						
DIC:	21,987.000						
MSPE:	2.767						

Table 8: Multivariate Tobit estimates of fed cattle parameters

Variables	DMFC		ADG		VCPH		MORT	
	coeff.	se.	coeff.	se	coeff.	se	coeff.	se
Intercept:	-1.208*	0.035	-2.684*	0.288	8.490*	0.178	24.001*	1.447
Steers:	-0.092*	0.001	-0.083*	0.012	0.431*	0.007	0.141*	0.052
Mixed:	-0.028*	0.002	0.152*	0.020	0.134	0.011	0.556*	0.098
Kansas:	-0.137*	0.002	-0.253*	0.013	0.251*	0.007	-0.006	0.061
log(inwt):	0.481*	0.005	0.806*	0.044	-0.822*	0.027	-3.605*	0.221
Winter:	0.011*	0.002	0.003	0.014	-0.269*	0.008	-0.041	0.064
Fall:	0.069*	0.002	0.074*	0.014	-0.313*	0.008	0.126	0.070
Spring:	-0.022*	0.002	-0.164*	0.016	-0.020	0.008	-0.215*	0.065
Heteroskedasticity:								
Intercept:	-9.032*	0.787	-8.387*	0.790	6.534*	0.929	12.713*	1.116
Steers:	-0.038	0.036	-0.563*	0.036	0.117*	0.036	0.007	0.048
Mixed:	0.450*	0.054	-0.139*	0.056	0.242*	0.056	0.605*	0.070
Kansas:	-0.269*	0.042	0.236*	0.042	0.014	0.041	-0.041	0.057
log(inwt):	0.683*	0.122	1.048*	0.122	-1.433*	0.141	-1.742*	0.170
Winter:	-0.094*	0.045	0.075	0.046	0.082	0.046	-0.130*	0.061
Fall:	0.326*	0.045	0.170*	0.046	0.196*	0.046	0.209*	0.060
Spring:	-0.355*	0.046	0.511*	0.051	0.126*	0.047	-0.124	0.065
Covariance(t):								
Cov(DMFC VCPH:)			1.254*	0.054				
Cov(DMFC MORT:)			7.503*	0.254				
Cov(DMFC ADG:)			-4.090*	0.031				
Cov(VCPH MORT:)			1.039*	0.053				
Cov(VCPH ADG:)			-0.094*	0.006				
Cov(ADG MORT:)			0.003	0.002				
LL:			-15,748.2					
AIC:			31,636.5					
DMFC MSPE:			0.009					
VCPH MSPE:			0.232					
ADG MSPE:			0.216					
MORT MSPE:			2.617					

*Denotes the estimate is statistically significant at the 0.05 level

Table 9: Multivariate ZILN estimates of fed cattle parameters

Variables	DMFC		ADG		VCPH		MORT	
	coeff.	se.	coeff.	se	coeff.	se	coeff.	se
Intercept:	0.767*	0.048	-2.091*	0.160	11.000*	0.215	11.220*	0.144
Steers:	-0.069*	0.002	0.322*	0.010	0.073*	0.012	0.094*	0.021
Mixed:	-0.030*	0.004	0.150*	0.016	0.218*	0.019	0.359*	0.034
Kansas:	-0.121*	0.002	0.186*	0.012	-0.207*	0.012	0.111*	0.027
log(inwt):	0.178*	0.007	0.794*	0.025	-1.289*	0.033	-1.707*	0.022
Winter:	-0.002	0.003	-0.193*	0.013	-0.073*	0.013	-0.020	0.027
Fall:	0.052*	0.003	-0.242*	0.014	0.016	0.013	0.047	0.027
Spring:	-0.017*	0.003	-0.054*	0.013	-0.083*	0.014	-0.044	0.028
Heteroskedasticity:								
Intercept:	-1.606*	0.251	-7.182*	0.196	-2.983*	0.250	-0.357	9.925
Steers:	-0.397*	0.026	0.253*	0.066	-0.045	0.060	-0.002	10.210
Mixed:	0.123*	0.040	0.365*	0.075	0.092	0.080	-1.067	10.210
Kansas:	0.148*	0.030	-0.155*	0.051	-0.207*	0.053	-1.876	9.530
log(inwt):	-0.504*	0.038	0.790*	0.028	-0.271*	0.032	-9.971*	5.932
Winter:	0.160*	0.032	-0.189*	0.056	-0.120	0.063	0.322	10.720
Fall:	0.313*	0.032	0.194*	0.056	0.047	0.063	-0.018	9.713
Spring:	0.332*	0.037	-0.300*	0.069	-0.164*	0.070	-0.167	9.724
Delta:								
Intercept:							-16.060*	0.360
Steers:							-0.062	0.049
Mixed:							-0.181*	0.081
Kansas:							0.108	0.062
log(inwt):							2.402*	0.055
Winter:							-0.051	0.064
Fall:							-0.082	0.067
Spring:							0.152*	0.065
Covariance(t):								
Cov(DMFC VCPH:)			4.696*	0.061				
Cov(DMFC MORT:)			1.841*	0.113				
Cov(DMFC ADG:)			-1.742*	0.185				
Cov(VCPH MORT:)			6.720*	0.584				
Cov(VCPH ADG:)			0.483	0.401				
Cov(ADG MORT:)			0.059	0.105				
LL:			-9,617.8					
DIC:			19,348.0					
DMFC MSPE:			0.008					
VCPH MSPE:			0.182					
ADG MSPE:			0.170					
MORT MSPE:			1.296					

*Denotes the estimate is statistically significant at the 0.05 level

Table 10: Multivariate ZILN model fit estimates, by element

Variable	Dbar	Dhat	pD	DIC	LL
ADG	7,923.6	7,911.5	12.1	7,935.7	-3,955.8
DMFC	-15,002.6	-15,013.3	10.7	-14,991.8	7,506.7
MORT	7,195.6	7,179.1	16.5	7,212.0	-3,589.6
VCPH	8,964.0	8,954.1	9.9	8,973.9	-4,477.1
D	10,211.2	10,204.2	7.0	10,218.2	-5,102.1
total	19,291.8	19,235.6	56.2	19,348.0	-9,617.8