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5 Posters

Optimal credible intervals under alternative loss functions

Intervalli di credibilità ottimi per diverse funzioni di perdita

Fulvio De Santis and Stefania Gubbiotti

Abstract This article deals with Bayesian interval estimation of the parameter of a statistical model from a decision-theoretic perspective. We consider the class of monotone loss functions, that take into account both size and posterior probability of the sets and that, under general conditions, guarantees the optimality of highest posterior probability sets. More specifically, we focus on three families of loss functions: linear, rational and exponential. Resorting to numerical examples and simulations, we examine both posterior and pre-posterior features of these choices for the Poisson-Gamma model.

Abstract *Questo articolo riguarda la stima intervallare bayesiana del un parametro incognito di un modello statistico in un'ottica decisionale. La classe delle funzioni di perdita monotone coinvolge sia la dimensione degli insiemi sia la loro probabilità a posteriori. Sotto condizioni generali questa classe garantisce l'ottimalità degli insiemi HPD (highest posterior density). In particolare, questo lavoro si concentra su tre famiglie di funzioni di perdita: lineare, razionale ed esponenziale. Mediante esempi numerici e simulazioni viene condotta un'analisi a posteriori e un'analisi predittiva delle caratteristiche delle diverse funzioni di perdita per il modello Poisson-Gamma.*

Key words: Bayesian inference, credible sets, decision theory, interval estimation, loss functions, sample size determination, set estimation.

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1 Introduction

Given a parametric model, $\{f_n(\cdot|\theta),\ \theta \in \Theta\}$, let $\pi(\theta)$ denote the prior distribution of θ, $\mathbf{x}_n$ an observed sample of size n and $\pi(\theta|\mathbf{x}_n)$ the corresponding posterior distribution. For simplicity, suppose that $\Theta \subseteq \mathbb{R}^1$ and that $\pi(\theta)$ is a probability density function. Assuming to be interested in set estimation of θ from a decision theoretic perspective (see [1] and [4]), let $\mathscr{C}$ be a class of subsets of Θ and $\mathbb{L}(\theta, C)$ the loss function for a generic set $C \in \mathscr{C}$. This approach prescribes one to select a set $C^\star$ that minimizes the posterior expected loss $\rho(C, \mathbf{x}_n)$ as C varies in $\mathscr{C}$, i.e:

$$C^\star = \arg\min_{C \in \mathscr{C}} \rho(C, \mathbf{x}_n), \quad \text{where} \quad \rho(C, \mathbf{x}_n) = \int_\Theta \mathbb{L}(\theta, C)\pi(\theta|\mathbf{x}_n)d\theta.$$

The most widely used family of losses for set estimation is defined by setting

$$\mathbb{L}(\theta, C) = \mathbb{S}[\mathscr{L}(C)] + \mathbb{I}_{\bar{C}}(\theta), \tag{1}$$

where the *size* $\mathbb{S}(\cdot)$ is an increasing function of $\mathscr{L}(C)$ - the Lebesgue measure of C - and $\mathbb{I}_{\bar{C}}(\cdot)$ is the indicator function of the set $\bar{C} = \Theta \setminus C$. The resulting posterior expected loss of $C \in \mathscr{C}$ is

$$\rho(C, \mathbf{x}_n) = \mathbb{S}[\mathscr{L}(C)] + 1 - \mathbb{P}(C|\mathbf{x}_n),$$

which embodies a compromise between the size of C and its posterior probability of containing θ, denoted as $\mathbb{P}(C|\mathbf{x}_n)$. One important property of the class of monotone functions (see, for instance, [3]) is that, if θ is an absolutely continuous random variable (as we assume here), optimal actions are HPD sets defined as $C^\star = \{\theta \in \Theta\ :\ \pi(\theta|\mathbf{x}_n) \geq k\}, k \geq 0\}$. More specifically, we here assume that HPD sets are intervals $C = [L, U]$ and that $\mathscr{L}(C) = U - L$ is the length of C. The simplest form of loss (1) is obtained by selecting

$$\mathbb{S}_\ell[\mathscr{L}(C)] = a\mathscr{L}(C), \quad a > 0, \tag{2}$$

as size function, which yields the class of *linear* loss functions, $a\mathscr{L}(C) + \mathbb{I}_{\bar{C}}(\theta)$. Casella, Hwang and Robert in [2] and [3] show that, in the case of unbounded parameter space, optimal sets under the linear loss function may be dominated by unreasonable sets. For instance, in the case of the normal model $\mathrm{N}(\theta, \sigma^2)$ with unknown variance, the standard Student's t-interval for θ is dominated by a set that is empty as the sample variance is sufficiently large. They also show that (under mild conditions) these kinds of problems are avoided if both the components of (1) assume values in $[0,1]$ or, more specifically, if $\mathbb{S}(\cdot)$ is a nonlinear and increasing function that ranges monotonically in the unit interval and $\lim_{A \to \emptyset} \mathbb{S}(A) = 0$ and $\lim_{A \to \Theta} \mathbb{S}(A) = 1$. To resolve the paradox observed in the normal model, the authors propose some nonlinear functions $\mathbb{S}(\cdot)$. Among these, they consider

$$\mathbb{S}_e[\mathscr{L}(C)] = 1 - e^{-\frac{a\mathscr{L}(C)^2}{2}} \qquad \text{and} \qquad \mathbb{S}_r[\mathscr{L}(C)] = \frac{a\mathscr{L}(C)}{a\mathscr{L}(C) + 1}, \qquad a > 0 \tag{3}$$

that result in the class of *exponential* and *rational* loss functions. The posterior expected losses corresponding to the three size functions under examination in this article are then given by:

$$\rho_j(C, \mathbf{x}_n) = \mathbb{S}_j[\mathscr{L}(C)] + 1 - \mathbb{P}(C|\mathbf{x}_n), \qquad j = \ell, e, r \tag{4}$$

In [2] and [3] ρ_e and ρ_r were originally introduced and motivated for the normal model. We here explore their behavior for the Poisson-Gamma model.

The article is organized as follows. In Section 2 we consider numerical examples to investigate the impact on optimal actions of the choice of the size function and of the coefficient a, which controls the degree of penalization of intervals length. In Section 3, we adopt a pre-posterior point of view and compare optimal actions to usual intervals with fixed credibility, using the three different loss functions. Section 4 contains some concluding remarks.

2 Posterior comparison of loss functions

Let $X_i|\theta \sim \mathrm{Pois}(\theta)$, $i = 1, \ldots, n$ (i.i.d.), $\theta > 0$ and $\theta \sim \mathrm{Ga}(\alpha, \beta)$, $\alpha, \beta > 0$. Then, from standard results $\theta|\mathbf{x}_n \sim \mathrm{Ga}(\bar{\alpha}, \bar{\beta})$, where $\bar{\alpha} = \alpha + s_n$, $\bar{\beta} = \beta + n$ and $s_n = \sum_{i=1}^{n} x_i$. For each loss function and for selected values of a we determine the optimal sets $C^\star$ using the following numerical procedure. We consider a grid of values for $\gamma = \mathbb{P}(C|\mathbf{x}_n) \in (0,1)$. For each value of γ we determine C_γ, the HPD interval for θ using the R function `HDInterval::hdi` and compute $\rho_j(C_\gamma, \mathbf{x}_n)$. Then, we select $\gamma^\star$ as the minimizer of $\rho_j(C_\gamma, \mathbf{x}_n)$. Figure 1 shows the plots of $\rho_j(C_\gamma, \mathbf{x}_n)$ as functions of γ for Gamma posteriors of parameters $(\bar{\alpha}, \bar{\beta}) = (6,2)$ (left column) and $(\bar{\alpha}, \bar{\beta}) = (14,2)$ (right column). For each value of a the selected $\gamma^\star$ is circled. As a consequence of the mathematical structure of $\mathbb{S}_j$, for $j = \ell, e$, the larger a the smaller $\gamma^\star$ for both the linear and the exponential loss functions, whereas this is not true for the rational loss. As expected $\rho_\ell(C_\gamma, \mathbf{x}_n)$ is highly sensitive to the values of a. Hence the range of $\gamma^\star$ is the highest among the three loss functions. Conversely, values $\gamma^\star$ for $\rho_r(C_\gamma, \mathbf{x}_n)$ are substantially unaffected by the choice of a, that however influences the minimum values $\rho_r(C^\star, \mathbf{x}_n)$. They invariably bring $C^\star$ with posterior probability close to the conventional level 0.95, thus revealing an excessive robustness with respect to a. Finally, the exponential loss seems to represent a sensible trade-off between the two other competitor loss functions. Table 1 reports the values of $\mathscr{L}(C^\star)$, $\mathbb{P}(C^\star|\mathbf{x}_n)$ and $\rho_j(C^\star, \mathbf{x}_n)$ for optimal intervals $C^\star$. Even though the role of a, namely the coefficient that penalizes the length of the intervals, is not equivalent in the different size functions $\mathbb{S}_j$, a look at their effect on the resulting $C^\star$ and related quantities is still informative: the larger a, the smaller $\mathscr{L}(C^\star)$ and $\mathbb{P}(C^\star|\mathbf{x}_n)$, the larger the corresponding $\rho_j(C^\star, \mathbf{x}_n)$. This effect is mostly remarkable in the linear loss case. The variations in the values of $\rho_r(C^\star, \mathbf{x}_n)$ depend almost entirely on the values of a, whereas $\rho_\ell(C^\star, \mathbf{x}_n)$ and $\rho_e(C^\star, \mathbf{x}_n)$ change according to $\mathscr{L}(C^\star)$ and $\mathbb{P}(C^\star|\mathbf{x}_n)$.

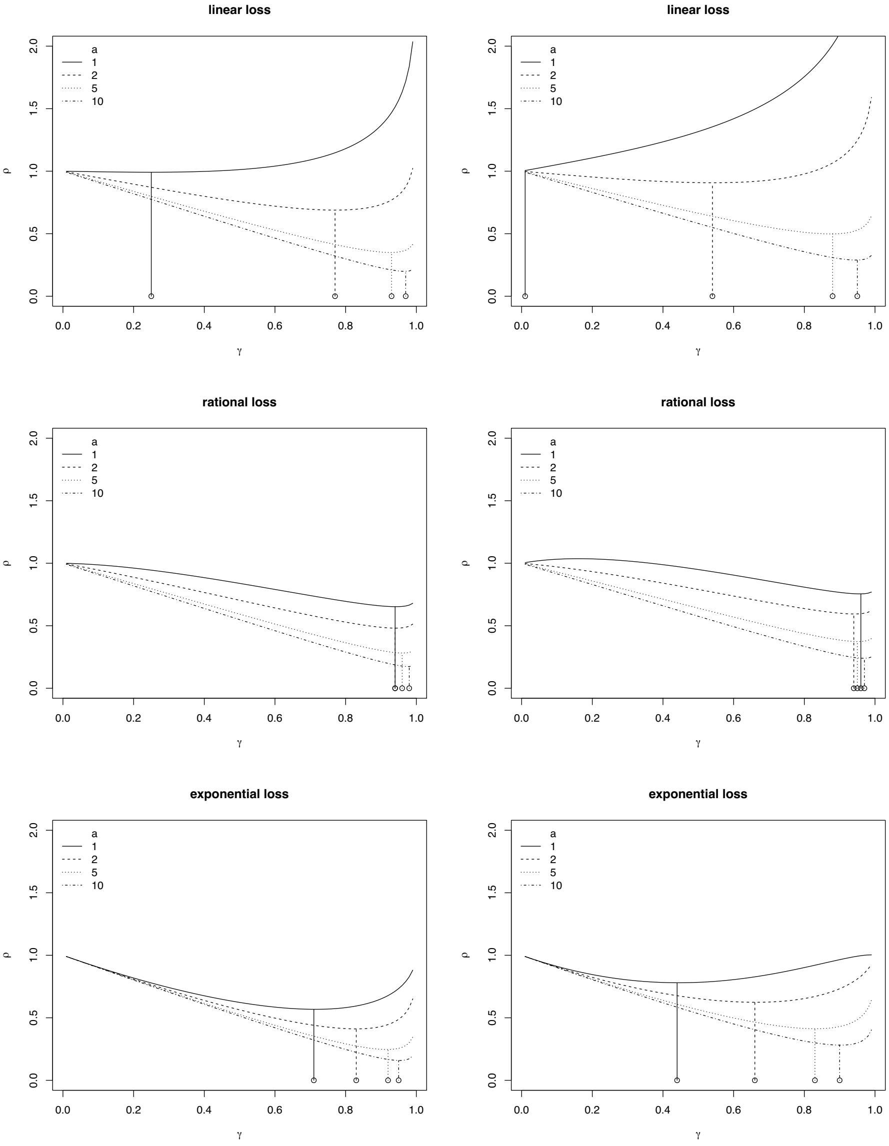

Fig. 1 Posterior expected losses $\rho_j(C, \mathbf{x}_n),\ j = \ell, r, e$, as functions of $\mathbb{P}(C|\mathbf{x}_n)$ for different values of a for Gamma posteriors of parameters $(\bar{\alpha}, \bar{\beta}) = (6, 6)$ (left column) and $(\bar{\alpha}, \bar{\beta}) = (14, 6)$ (right column). For each $\rho_j,\ j = \ell, r, e$, circles denote $\mathbb{P}(C^{\star}|\mathbf{x}_n)$, i.e. the posterior probabilities of optimal sets.

Loss	a	$\mathscr{L}(C^\star)$	$\mathbb{P}(C^\star\|\mathbf{x}_n)$	$\rho_j(C^\star,\mathbf{x}_n)$	$\mathscr{L}(C^\star)$	$\mathbb{P}(C^\star\|\mathbf{x}_n)$	$\rho_j(C^\star,\mathbf{x}_n)$
		$(\bar{\alpha},\bar{\beta})=(6,6)$			$(\bar{\alpha},\bar{\beta})=(14,6)$		
linear	1.0	0.242	0.250	0.992	0.015	0.010	1.005
	0.5	0.917	0.770	0.689	0.895	0.540	0.907
	0.2	1.399	0.930	0.350	1.890	0.880	0.498
	0.1	1.689	0.970	0.199	2.390	0.950	0.289
rational	1.0	1.454	0.940	0.652	2.507	0.960	0.755
	0.5	1.454	0.940	0.481	2.292	0.940	0.594
	0.2	1.594	0.960	0.282	2.390	0.950	0.373
	0.1	1.817	0.980	0.174	2.652	0.970	0.240
exponential	1.0	0.807	0.710	0.568	0.706	0.440	0.780
	0.5	1.051	0.830	0.411	1.156	0.660	0.624
	0.2	1.350	0.920	0.247	1.667	0.830	0.412
	0.1	1.518	0.950	0.159	2.001	0.900	0.281

Table 1 Bounds, length, posterior probability and posterior expected loss for $C^\star$ under the three loss functions for selected values of a.

θ_d	n	$\mathbb{E}(\mathscr{L})$	$\mathbb{E}(\mathbb{S})$	$\mathbb{E}(\rho_e)$	$\mathbb{E}[\mathbb{P}(\cdot\|\mathbf{x}_n)]$
			(i)		
2	4	1.142	0.278	0.575	0.703
	10	1.072	0.250	0.430	0.820
	100	0.606	0.088	0.118	0.970
10	4	0.807	0.151	0.860	0.291
	10	1.019	0.229	0.775	0.454
	100	0.966	0.208	0.328	0.880
			(ii)		
2	4	2.178	0.687	0.737	0.950
	10	1.574	0.461	0.511	0.950
	100	0.548	0.072	0.122	0.950
10	4	4.290	0.988	1.038	0.950
	10	3.319	0.934	0.984	0.950
	100	1.217	0.310	0.360	0.950
			(iii)		
2	4	2.594	0.787	0.837	0.950
	10	1.716	0.519	0.569	0.950
	100	0.553	0.074	0.124	0.950
10	4	6.128	1.000	1.050	0.950
	10	3.904	0.976	1.026	0.950
	100	1.239	0.319	0.369	0.950

Table 2 Monte Carlo approximations of predictive expectations of length, size, posterior expected loss ρ_e and probability of *(i)* $C^\star$ and *(ii)* $C^\star_\gamma$ with an informative prior Gamma$(4,2)$ and *(iii)* $C^\star_\gamma$ with a non-informative prior Gamma$(0,0)$, for different values of n and θ_d.

3 Predictive comparison of optimal sets under exponential loss

In this section we focus on credible intervals optimal that are under the exponential loss, which has shown the most promising results in the explorative analysis of Section 2. For the sake of brevity we select the case $a = 0.5$. We consider a pre-posterior comparison between (i) optimal credible sets $C^\star$ and two conventional optimal credible intervals: HPD intervals $C^\star_\gamma$ of fixed credibility $\gamma = 0.95$, respectively obtained assuming (ii) the same prior $\mathrm{Gamma}(4,2)$ which yields $C^\star$; (iii) the non-informative $\mathrm{Gamma}(0,0)$. In Table 2 the three intervals are compared in terms of the predictive expected values $\mathbb{E}(\cdot)$ of their length, size function, posterior expected loss and probability. For simplicity, as predictive distribution we assume the sampling distribution $f_n(\cdot|\theta_d)$, where θ_d is a design value. The simulation steps are the following: draw M samples of size n from $f_n(\cdot|\theta_d)$; for each sample repeat the minimization described in Section 2 to derive $C^\star$ and compute $C^\star_\gamma$; for each of the three intervals determine $\mathscr{L}$, $\mathbb{S}$, ρ_e and $\mathbb{P}(\cdot|\mathbf{x}_n)$; compute the Monte Carlo means of $\mathscr{L}$, $\mathbb{S}$, ρ_e and $\mathbb{P}(\cdot|\mathbf{x}_n)$.

As a first comment note that, by construction, the values of $\mathbb{E}[\mathbb{P}(\cdot|\mathbf{x}_n)]$ are variable for (i) and fixed for (ii) and (iii). As expected, $C^\star$ outperforms $C^\star_\gamma$ (ii) and (iii) in terms of ρ_e. In the cases of low values for $\mathbb{E}[\mathbb{P}(C^\star|\mathbf{x}_n)]$ a gain in terms of expected length (and size function) is observed. In addition, whereas for the smallest value of θ_d the optimal set $C^\star$ guarantees a sufficiently large expected posterior probability for all sample sizes, for $\theta_d = 10$ the posterior probability of $C^\star$ may be excessively small (e.g. 0.291 for $n = 4$), unless the sample size is sufficiently large (e.g. 0.888 for $n = 100$). Finally, note the uniformly better performance of $C^\star_\gamma$ (ii) with respect to $C^\star_\gamma$ (iii) and their substantial equivalence for $n = 100$.

4 Conclusions

In this work in addition to the most widely used linear loss, we examine two alternative monotone loss functions for set estimation, previously proposed for the normal model. Monotonicity guarantees that, under mild conditions, optimal credible intervals are HPD sets. In the preliminary numerical comparisons of Section 2, the exponential loss seems to have an intermediate behavior with respect to the linear loss (highly sensitive to the choice of a) and the rational loss (excessively robust with respect to a). Pre-posterior analysis of ρ_e suggests that, in order to obtain optimal sets with sensible posterior probability, attention has to paid to the selection of the sample size.

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