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Functional Horvitz-Thompson estimator for convex curves

Stimatore di Horvitz-Thompson di curve convesse

Adelia Evangelista, Francesca Fortuna, Stefano Antonio Gattone, Tonio Di Battista

Abstract The work presents the Horvitz-Thompson estimator of convex curves in a functional setting. In many application fields, such as the analysis of Lorenz curves, or diversity profiles, practitioners work with convex curves. In such cases, a naive application of the Horvitz-Thompson functional estimator can lead to non-convex estimates. Thus, a constrained Horvitz-Thompson estimator for convex curves is introduced by defining these functions as a solution of a differential equation. A suitable sampling distribution of the proposed mean estimator has been derived, allowing to build simultaneous confidence bands, whose performance has been assessed by means of a simulation study.

Abstract *Il lavoro presenta lo stimatore di Horvitz-Thompson di curve convesse in un contesto funzionale. In molti ambiti applicativi, come nel caso delle curve di Lorenz o dei profili di diversità, si considerano curve convesse. Un'applicazione diretta dello stimatore funzionale di Horvitz-Thompson può condurre a stime non convesse. A tal fine, viene proposto uno stimatore di Horvitz-Thompson vincolato per curve convesse, definendo queste ultime come una soluzione di un'equazione differenziale. È stata ricavata un'opportuna distribuzione campionaria dello stimatore proposto, che consente di costruire bande di confidenza simultanee, valutate mediante uno studio di simulazione.*

Key words: Functional Horvitz-Thompson, Confidence bands, Convex curves

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1 Introduction

This work reports the main results of a recent paper [10]. The aim is to obtain a constrained functional Horvitz-Thompson estimator in a design-based inference context. The basic motivation was that in several application fields such as income inequality [17], biological diversity [6, 7], ecology [5], industrial concentration [11], reliability [4] and disease risks [13], researchers work with convex curves. Example of convex curves are the Lorenz curve [12] in economics and the diversity profile [9] in ecology.

In order to build an estimator of the mean of convex curves in the functional domain two main topics need to be considered. The first one is related to the application of common methodologies of functional data analysis (FDA) in the presence of shape constraints, such as convexity [8]. FDA techniques usually require that functions have value in the separable Hilbert space of square integrable functions, known as $L^2(\mathcal{X})$, with the inner product $\langle f, g \rangle = \int_{\mathcal{X}} f(x)g(x) dt, \forall f, g \in L^2(\mathcal{X})$, and the L^2 norm $\|f\| = \langle f, f \rangle^{1/2} < \infty$. The second matter regards the use of FDA in a design-based inference setting. In 2010s, Cardot et al. [1] investigated this issue by studying the theoretical properties of functional principal components when the curves are collocated with survey sampling techniques. Specifically, Cardot and Josserand [2] presented a Horvitz-Thompson estimator for functional data, under the hypothesis of error-free measurements. Later, this assumption was removed, estimating the data with local polynomials [3].

Gattone et al. [10] expanded the Cardot's approach to convex functions. The work focuses on the estimation of the Lorenz curve in a designed-based approach. As it is well known, the family of Lorenz curves are constrained to be non-negative, bounded, increasing and convex. In this framework, a suitable transformation of the Lorenz curve is proposed, using the differential equation approach introduced by Ramsay in 1998 [15]. In this way, the estimation is performed in the unconstrained $L^2(\mathcal{X})$ space. The resulting constrained Horvitz-Thompson estimator is biased for finite samples with an unknown distribution. Therefore a delta method procedure is implemented for reducing the bias, and to get a consistent and asymptotically normal estimator. Thus, confidence bands could be constructed by means of simulations of functional Gaussian processes based on the estimated covariance function.

The reminder of the work proceeds as follows. In Sect. 2 we derive the functional Horvitz-Thompson estimator of Lorenz curve with its asymptotic confidence bands. Sect. 3 describes the results of the simulation study, and conclusions are presented in Sect. 4.

2 Functional Horvitz-Thompson estimation of Lorenz curve

As outlined in Sect. 1, the aim of this work is to provide a consistent Horvitz-Thompson estimator of the Lorenz curve in a design-based approach. The first step is to move the observed Lorenz curves into a suitable functional space. To this end,

the differential equation approach proposed by Ramsay in 1998 [15] and previously adopted by Fortuna et alv[9] has been applied.

The Lorenz curve can be expressed as follows:

$$f(p) = CD^{(m-1)} \exp\left(D^{-1}w(p)\right), \quad 0 \leq p \leq 1, \quad (1)$$

that is as the solution of the differential equation $D^m f(p) = w(p)D^{m-1}f(p)$, where D^m is the m -th derivative of $f(p)$, $D^{-1}w(p) = \int_0^p w(s)ds$ represents the partial integration operator and $w(p)$ indicates an unconstrained function [10]. We set $C = \frac{1}{D^{-2} \exp(D^{-1}w_1)}$, in order to ensure that $f(1) = 1$. It is easy to prove that $f(p)$ in Eq. (1) is a convex curve when $m = 3$ [15]. The unconstrained function $w(p)$ can be written as a linear combination of basis functions:

$$w(p) = \sum_{b=1}^B c_b \phi_b(p), \quad (2)$$

where c_b stands for the b -th coefficient and $\phi_b(p)$ is the b -th basis function and $w(p)$ lies in the Hilbert space, $L^2(\mathcal{X})$. Then, the Lorenz curve can be rewritten in the constrained functional form by putting $w(p)$ in Eq. (1).

The procedure follows with the definition of the Horvitz-Thompson (HT) estimator for the mean of convex curves. Starting from the HT estimator introduced in [2] and [3], the unconstrained functional HT estimator of the mean is defined as follows:

$$\bar{w}_{HT}(p) = \frac{1}{N} \sum_{i \in s} \frac{w_i(p)}{\pi_i} = \frac{1}{N} \sum_{i \in s} \frac{\sum_{b=1}^B c_{bi} \phi_b(p)}{\pi_i}, \quad (3)$$

where N is the size of the finite population U , $\{w_i(p)\}_{p \in [0,1]}$ is the unique function associated to each i -th unit $\in U$, π_i are the first order inclusion probabilities and $s \in U$ is the selected sample of size n .

Including in Eq. (1) the estimator defined in (3), it is possible to construct the constrained HT estimator of the mean of convex curves as follows:

$$\bar{f}_{HT}(p) = \bar{C} D^{-2} \exp\left(D^{-1} \bar{w}_{HT}(p)\right). \quad (4)$$

with $\bar{C} = \frac{1}{D^{-2} \exp(D^{-1} \bar{w}_{HT}(1))}$.

Finally, the application of the delta method allows the evaluation of the bias as follows:

$$\widehat{bias}(\bar{f}_{HT}(p)) = \frac{1}{2n^2} \left[g''(\bar{w}(p)) \right] \hat{\gamma}(p, p'), \quad (5)$$

where g stands for a non-linear function, $p \in [0, 1]$, $g''(\bar{w}(p))$ defines the second derivative and $\hat{\gamma}(p, p')$ is the covariance function of the unconstrained estimator.

Moreover from [14], it follows:

$$\sqrt{n} \left\{ g(\bar{w}_{HT}(p)) - g(\bar{w}(p)) \right\} \xrightarrow{d} \mathcal{N} \left(0, \left[g'(\bar{w}(p)) \right]^2 \gamma(p, p') \right), \quad \forall p \in [0, 1]. \quad (6)$$

From this result it is possible to derive the pointwise confidence interval as follows:

$$P \left(\bar{f}_{HT}(p) \in \left[\bar{f}_{HT}^*(p) \pm q_\alpha \sqrt{\text{Var}(\bar{f}_{HT}^*(p))} \right] \right) = 1 - \alpha, \quad \forall p \in [0, 1], \quad (7)$$

where q_α is the quantile of order $1 - \alpha/2$ of the standard Normal distribution, and $\text{Var}(\bar{f}_{HT}^*(p)) = \left[g'(\bar{w}(p)) \right]^2 \hat{\gamma}(p, p')$.

Simultaneous confidence bands for the HT estimator are derived for the entire domain at once by:

$$P \left(\bar{f}_{HT}(p) \in \left[\bar{f}_{HT}^*(p) \pm c_\alpha \sqrt{\text{Var}(\bar{f}_{HT}^*(p))} \right], \quad \forall p \in [0, 1] \right) = 1 - \alpha, \quad (8)$$

defining c_α as an approximation of the supremum of a Gaussian process [3].

3 Simulation study

A simulation study is implemented to assess the behaviour of the Functional Horvitz-Thompson estimator of Lorenz curve proposed. All the computational aspects have been implemented through the R software [16].

Using a generalized distribution of second kind (GB2) the income vector of a finite population of 50000 units have been generated. Then, we consider three scenarios with different level of income inequality, which are respectively Low, Medium and High concentration (see [10] for more details).

In Fig.1 the pointwise empirical coverage are shown. The results highlight a good behaviour in the low concentration scenario, with the pointwise empirical coverage always between 0.9 and 1. Considering the Medium and High scenario, for $p > 0.8$ the coverage declines, indicating a worse behaviour in the final part of the curve.

The simultaneous empirical coverage is reported in Table 1. The values obtained confirm a conservative behaviour in the case of the Low concentration; in the Medium concentration scenario the empirical level equalizes the nominal coverage and for the High scenario there is a moderate under-coverage.

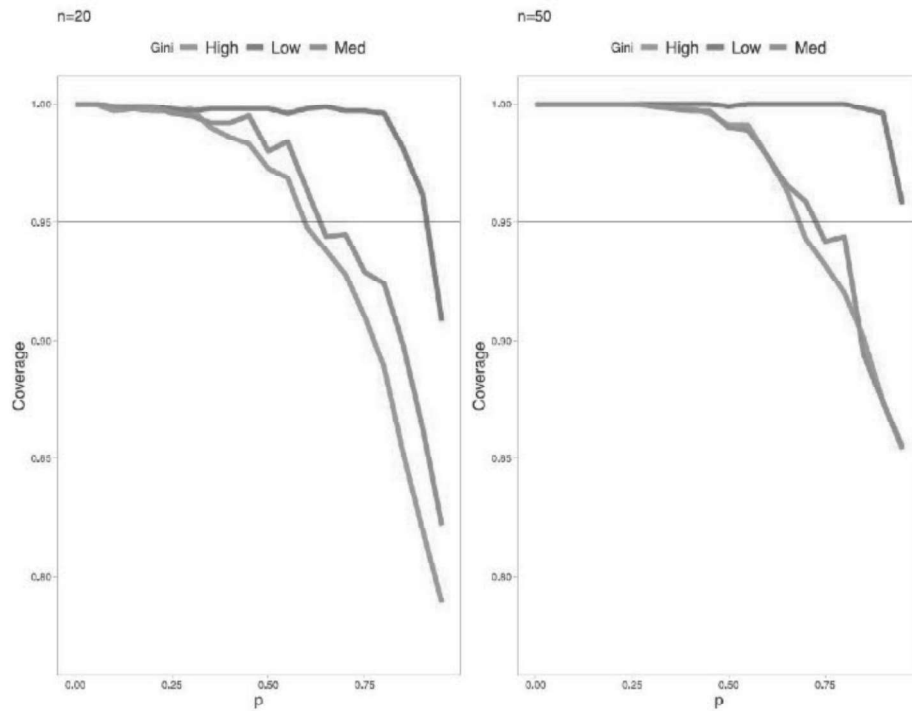


Fig. 1 Pointwise empirical coverage. Nominal level $1 - \alpha = 0.95$.

Table 1 Empirical coverage of the *SCB* simultaneous confidence bands under different scenarios and sample size. Nominal level $1 - \alpha = 0.95$.

Scenario	n	<i>SCB</i>
Low	20	0.99
concentration	50	0.99
Medium	20	0.95
concentration	50	0.96
High	20	0.91
concentration	50	0.92

4 Conclusion

The main results of a recent paper appeared on *Econometrics and Statistics* have been presented. In particular the functional Horvitz-Thompson estimator of Lorenz curve has been derived. Theoretical results have been derived and a simulation study has been implemented in order to evaluate the performance of the proposed procedure. Results show a good performance of the estimator. Future works will focus on to more complex constrained indicators both in social and ecological fields.

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