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Assessing the stochastic variability of the Benefit-Cost ratio in roadway safety management

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ABSTRACT

Road Agencies set quantitative targets and adopt related road safety strategies within the priorities and the available resources at the time of an economic crisis. In this framework, benefit-cost analyses (BCA) are carried out to support the decision making process and alternative measures are ranked according to their expected benefit and benefit-cost ratio calculated using a Safety Performance Function (SPF) and Crash Modification Factors (CMFs) as predictors of future safety performances.

Due to the variance of CMFs and crash frequency we are uncertain what the benefits of some future actions will be. The chance of making wrong decisions depends on the size of the standard deviation of the probability distribution of the considered stochastic variables.

To deal with the uncertainty inherent in the decision making process, a reliability based assessment of benefits must be performed introducing a stochastic approach. In the paper the variability of the CMFs, the predicted number of crashes and the crash costs are taken into account in a reliability based BCA to address improvements and issues of an accurate probabilistic approach when compared to the deterministic results or other approximated procedures. A case study is presented comparing different safety countermeasures selected to reduce crash frequency and severity on sharp curves in motorways. These measures include retrofitting of old safety barriers, delineation systems and shoulder rumble strips. The methodology was applied using the Monte Carlo simulations to calculate the probability of failure of BCA statements. Results and comparisons with alternative approaches, like the one proposed in the HSM, are presented showing remarkable differences in the evaluation of outcomes which can be achieved.

1. Introduction

The decision-making process for safety interventions is complex, involving a number of actors (e.g. experts, public, politicians, etc.) and issues (e.g. environment, economy, congestion) competing for the scarce available resources. The risk of making poor decisions and the cost of making better decisions can be reduced by the use of reliable studies on how effective different safety measures are (OECD and ITF, 2012). In this framework, Road Agencies set specific quantitative safety targets and adopt related road safety strategies towards these targets, within the established priorities and the available resources. In particular, benefit-cost analyses are carried out in a more-or-less systematic way, at the national, regional or local level, to maximise results within the limited available funds.

The Benefit-Cost analysis (BCA) aims to compare the benefits and costs of different policy alternatives, measured in monetary units. Measures for which benefits are greater than costs are called cost-effective, and ranked according to their benefit-cost ratio.

The BCA essentially requires three different estimates:

1. an estimate of the safety problem, i.e. crash frequency and typology based on crash history and/or Safety Performance Function;
2. an estimate of the effectiveness, i.e. Crash Modification Factors (CMFs) of road safety measures available for solving the safety problem; and
3. an estimate of the comprehensive (social and damage) cost of crashes and cost of each measure.

The most important uncertainties involved in developing such an assessment process concern the adoption of appropriate values for the safety effects of road safety measures.

Scientific accuracy is difficult to obtain in the field of CMFs, not only because several assumptions are necessary in the process, but also because it is very difficult to separate the safety

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effect of a measure from the effect of several other microscopic or macroscopic measures and phenomena (including statistical randomness) occurring at the same place. Two main issues affect the reliability of CMFs: accuracy and transferability. The former factor pertains to the data quality, the small sample size, the bias and confounding factors not eliminated. The latter factor has to do with the fact that the CMF estimates come from studies conducted in differing circumstances that are not directly correlated to the CMF value by the way of a function. Hauer et al. (OECD and ITF, 2012) described how important is the site to site variability. Indeed, along with the uncertainties inherent in the estimation, the site to site variability is able to increase the value of the common considered variance considerably.

It is necessary to assess whether the studies can be generalised in time and space (external validity of research), e.g. from one country to another, or from one decade to another, showing the consistency in time and space of studies that have evaluated the effects of road safety measures (OECD and ITF, 2012; Shadish et al., 2002).

A framework for interpreting road safety evaluation studies in theoretical terms has been proposed by (Elvik, 2004). This framework is a conceptual scheme that can be used to develop arguments for or against the general validity of road safety studies.

A cumulative meta-analysis is well suited for assessing external validity based on the range of replications (OECD and ITF, 2012; Elvik et al., 2009), but the applicability of the technique is likely to be limited, and it can be applied to assess external validity when a large number of studies have been reported during a long period of time.

To make progress towards reducing the uncertainty about CMFs, a two-pronged strategy has to be followed. First, the CMF estimates used to produce the probability distributions have to be consistent. Secondly, the dependence of the CMFs on the relevant circumstances has to be established by way of a function (OECD and ITF, 2012).

Any future improvement in knowledge of the effectiveness of safety measures, i.e. a development of quality Crash Modification Functions, will probably have tangible effects on the way safety decisions are made. On the other hand, the development of new reliable CMFs is costly and time consuming. A typical project to develop a reliable CMF related to roadway features in the United States, for example, will cost about $200,000. Therefore, finding a way of using the current available CMFs is important in the short term, as well as developing new CMFs in the medium term.

In this context, it is necessary to account for the heterogeneity of study findings by considering that CMF is not a constant, but is instead a random variable. Thinking of a CMF as a random variable allows us to frame the question of accuracy and transferability of existing CMFs correctly.

Whether decisions are right or wrong depends on the size of the standard deviation of the probability distribution of the variable considered in the BCA. The smaller the standard deviations, the larger the probability that decisions are correct.

The HSM in Part A, Appendix C (Highway Safety Manual (HSM), 2010) treats the variance in CMF giving a procedure to evaluate the probability of failure (i.e. what the chance is that implementing the treatment is the wrong decision). The standard error of CMF is used to define a confidence interval that indicates the range of values that contain the true treatment effect with a given level of confidence. The interval limits CMF_k may be easily calculated, with approximation, using the formula that assumes a normal distribution of CMF, as suggested in the HSM using Eq. (1):

$$CMF_k = E(\theta) \pm k \times \sigma(\theta) \tag{1}$$

Where θ is the random variable associated with the probability density function of the CMF; E(θ) is the expected (mean) value of the CMF; σ(θ) is the standard error of the CMF; kα is the standardised normal variable with probability 1-α (e.g. 1.96 for α = 5%); 1-α is the confidence level (e.g. α = 5%).

Based on this approach, it would be reasonable, in the decision-making process, to give less consideration to treatments for which the associated CMF has a confidence interval that includes 1.0, meaning that there is a probability that crashes will remain unchanged or experience a slight increase (i.e. CMF > 1). Furthermore, it may be prudent in some situations to give greater consideration to treatments with smaller confidence intervals because of the greater level of certainty in the results. This procedure is simple and able to take into account the expected value of CMF and its variance as well. However, as will be shown later, it is not able to catch the whole variability of the phenomenon, which involves also the uncertainty in the estimation of crashes and crash cost and, as a consequence, variability in the estimation of benefits and benefit-cost ratio.

Another caveat should be made regarding the use of SPFs for assessing the impact of road safety measures, which typically require a forecast of the number of crashes and casualties several years ahead of the implementation year. Therefore, also the estimation of the future number of crashes plays a fundamental role in BCA. SPFs modelling, variance and transferability concerns are of the same nature and relevance of CMF. The application of the Highway Safety Manual (HSM) in Europe promotes the improvement and application of advanced safety performance analysis, tools and processes in highway design, but the use in EU countries of HSM models and calibration tools shows cause for concern for transferability as well (La Torre et al., 2014; D'Agostino, 2014; Cafiso et al., 2012; Sacchi et al., 2012). Calibration of new SPFs using local data improves the precision of the estimation, but the variability in the expected/predicted number of crashes persists and is a further cause of randomness to be considered in the BCA. Even when different crash severities are considered, the identification of benefit is challenging.

Here, both the variance of the CMFs and SPFs is taken into account in a reliability-based assessment of safety benefits to catch this variability, as a more rigorous probabilistic approach can lead to different conclusions about implementing or not implementing a treatment. First, the methodology framework is introduced; afterwards, a case study of reliability analysis is presented comparing different safety countermeasures on sharp curves in motorways. The methodology applied using Monte Carlo simulation and comparisons with traditional approaches point out the difference in the evaluation results that can be achieved (Cafiso and D'Agostino, 2015).

2. Methodology

Our methodology is now reported, presenting the general framework of the Benefit Cost Analysis (BCA), the probability distributions of all the factors involved in the BCA, and the numerical tool needed to apply the procedure to a real case study.

2.1. General approach to the benefit cost analysis

In the general form, the B/C ratio of a treatment is defined as follows:

$$\frac{B}{C} = \frac{\text{Benefits}}{\text{Cost}} = \frac{\lambda \cdot a \cdot \left(1-\theta\right)}{c} \tag{2}$$

where λ = number of target crashes on the unit in the reference time; θ = crash modification factor of the treatment; a = monetary value of a single crash; and c = cost of the treatment implementation.

To carry out a BCA using a stochastic approach, Eq. (2) has to be evaluated considering θ, λ and "a" as random variables and per-