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Uncertainty-based prioritization of road safety projects: An application of data envelopment analysis

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ABSTRACT

The use of ranking methods in safety retrofit projects, in order to reduce uncertainty to an acceptable level, is a crucial problem. This paper presents a multidimensional method for prioritizing safety retrofit projects, in which uncertainty is taken into account in benefits estimation (accident reduction) and costs. Data Envelopment Analysis (DEA) with uncertainty assessment is described to help decision makers select the most cost effective projects. It is different from other ranking methods in that this approach adds standard errors of crash modification factor and crash costs in selecting process as well as the average values. Furthermore, this model is applied to a sample of intersections that are required to improve safety. Results have revealed that the proposed model is a suitable tool in selecting efficient projects when tolerances in accident reductions and project cost are incorporated. Comparative study between the proposed model and incremental benefit cost analysis and integer programming methods has also indicated that some changes in the list of selected projects considering the uncertainty impacts of data were observed. This analysis allows such safety projects to be identified. This also provides more complete information for safety analysts to allocate a limit budget to more efficient safety projects.

1. Introduction

Prioritizing hazard sites and their countermeasures based on benefit or effectiveness is a significant part of literature in traffic safety research. Benefits of retrofit programs usually are associated with high costs for traffic authorities and society. Safety managers always are under increasing pressure to improve safety and reduce crashes while their budget is limited. Hence, ranking of projects is an inevitable necessity. In the ranking process cost effective projects are often chosen to render the best results from limited available resources (Montella, 2010). Better screening techniques and practices to introduce more efficient projects are needed with an extensive network of transportation, limited financial resources, and some problems such as lack of proper information.

The typical prioritization methods of retrofit projects include:

- Ranking based on economic effectiveness measures (such as net present value)
- Incremental benefit-cost analysis
- Optimization methods.

Ranking of projects by economic effectiveness measures or by the incremental benefit-cost analysis method is performed based on just a chosen criterion. Optimization methods such as linear or integer programming regard the impact of the budget constraints to find an optimized selection. (AASHTO, 2010). While all of these methods for prioritizing of projects have merit, they usually do not consider the multi-criteria nature of the problem and uncertainty of data and predictions.

Some studies have mentioned that uncertainty has an important effect on costs and benefits estimation and prioritization of projects. Elvik (2008a, 2010) has emphasized that safety analysts need to move towards reduction of uncertainty in costs and benefits of road safety treatments. He mentioned that due to resources of uncertainties, finding significant differences between previous estimations and actual outcomes of projects is not uncommon. Highway Safety Manual (AASHTO, 2010) has noted that wrong decision and chance of failure in benefits estimation of safety treatments go along with large variance in safety performance functions (SPFs) and crash modification factors (CMFs). Cafiso and Dagostino, 2015, with introducing an assessment method based on reliability and considering variance of CMF, have shown remarkable variation between results of their method and existent methods. Hermans et al. (2009) has recommended the use of uncertainty and sensitivity analysis in the selection of indicators and their method of weighting in ranking of countries safety situations.

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Uncertainty in estimating the monetary values of crashes or the relative value of accidents based on their severities (fatal, injury or property damage only (PDO)) are another sources of uncertainty (Council et al., 2005). UK Department for Transport (2007); Elvik (2008b) have reported different numbers for the relative importance of accidents. Geurts et al. (2004) have shown different weighting values to accidents based on severity has an important effect on black spots ranking. Also, due to the uncertainty associated with estimation of statistical life value and discounting problems of life and time, Hauer (2011) has shown that cost-benefit analysis cannot be a sufficient tool for prioritizing among projects.

Researchers have used optimization methods for prioritizing projects (Banihashemi, 2007; Harwood et al., 2004). However, the described problems by Hauer (2011) have still remained. Yu and Liu (2012) presented a multi-criteria model for ranking safety projects using the Analytical Hierarchy Process (AHP) method. They add a fuzzy scale level between the criteria level and the alternative level to reduce the uncertainty in judgments of decision makers. However, in this method uncertainty in synthesis of final scores for various alternatives and uncertainty in decision making process are also not considered.

Despite standard error being introduced as a sign of uncertainty in the various parts of safety research (such as calculation of CMFs, value of statistical crash, etc.), it is not commonly used in practical applications up to present.

This research proposes to use some uncertainties in decision making process, such as uncertainty in expected crash reduction, uncertainty in crash ratios based on severity (fatality, injury or PDO) and uncertainty in estimation of retrofit project cost to find a more optimized ranking. This will be done by using DEA with uncertainty assessment method.

In recent years, DEA has been used as an appropriate tool for evaluating and comparing in road safety fields. Cook et al. (2000) applied DEA for prioritization of safety treatment projects. They mentioned that different weights could be dedicated to different accident types from a road section to another by DEA method. Sadeghi et al. (2013) suggested DEA method in identifying and prioritizing accident prone road sections as it can consider the interaction of accidents as well as their casual factors such as traffic, geometric and environmental circumstances. Hermans et al. (2009); Shen et al. (2012) applied DEA to construct a composite index and to compare the safety situation of countries. Also, DEA method was applied for assessing the relative productivity of US states (Egilmez and McAvoy, 2013) and evaluating the efficiency of municipalities in providing traffic safety (Alper et al., 2015). Sala-Garrido et al. (2012) criticized that ranking by DEA methods are highly sensitive to data errors and therefore the role of uncertainty is of great importance.

León et al. (2003) applied the fuzzy mathematical programming for treatment of uncertainty in DEA models. After that, Bonilla et al. (2004) developed DEA model with uncertainty assessment for considering probable tolerances of inputs and outputs. In this method, an interval of efficiency scores is defined and prediction of efficiency will be possible when data are variable. Boscá et al. (2011) suggested a ranking method based on the statistical analysis of possible cases subsequent to computation of efficiency scores with existing tolerance in data.

This paper presents a procedure for prioritizing safety retrofit projects in a budget constrained area and considering uncertainty as tolerance in data inspired by what Bonilla et al. (2004); Boscá et al. (2011) suggested. In the next section, the suggested methodology of project ranking is described and traditional DEA is introduced followed by DEA with uncertainty assessment and prioritizing criteria. Section 3 presents an implicational example of intersections ranking; the results of this method will be compared with the ranking of incremental benefit-cost analysis and integer programming method. The last section contains some concluding remarks and suggestions for further research.

2. Methodology

2.1. Definition of problem

Road authorities have to prioritize the sites which require safety treatment due to budget limitations. To achieve this, benefits and costs of each treatment for each site should be determined and a ranking measure or method should be defined. Along with other possible benefits, reduced accidents due to implementation of a treatment are the most important benefits which are estimated as follows:

$$y_i = t_i(1-a_i) \tag{1}$$

where.

y_i = the expected number of reduced accidents by crash severity i.

t_i = the expected number of accident without the implementing countermeasure.

a_i = crash modification factor of treatment by crash severity i.

The total benefit can be estimated as

$$B = \sum_{i=1}^{K} \mu_i y_i \tag{2}$$

where μ_i is crash cost by severity i and B is monetary value of all reduced crashes. Also, benefits can be calculated by converting different types of accidents to equivalent property damage only accident (PDO) and multiplying PDO crash cost.

There are three types of uncertainty in the process of benefit estimation:

- Uncertainty with respect to the expected number of accidents.
- Uncertainty about CMFs of a countermeasure
- Uncertainty with respect to monetary values of different crashes.

So far, many efforts have been made to estimate the number of accidents. Empirical Bayesian (EB) method is accepted as a reliable method to estimate accident frequency in such a way that the variance of SPF as uncertainty is considered in the calculation process. (AASHTO, 2010; Persaud et al., 2010). Uncertainty of CMFs and crash costs are mentioned as standard errors in the literature (Council et al., 2005; AASHTO, 2010) and considering them in the calculation process may change the benefit values.

On the other hand, there are some uncertainties in the estimation of costs. While the cost of implementing countermeasure being the most important factor, there are additionally some other costs such as inconvenience of users. Occasionally, the estimated costs may significantly change along with fluctuations in price inflation or a considerable lapse between decision and execution times.

Accurate ranking may be affected by uncertainties in benefits and costs, hence more efficient projects may not be selected. Following sections describe the DEA with uncertainty assessment method for considering some uncertainties in the prioritization process and also demonstrate such uncertainty impacts on decision making area.

2.2. Classic data envelopment analysis

Data Envelopment Analysis (DEA) introduced by Charnes et al. (1978) is a method for measuring the relative performance or