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Improved hierarchical fuzzy TOPSIS for road safety performance evaluation

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ABSTRACT

With the ever increasing public awareness of complicated road safety phenomenon, much more detailed aspects of crash and injury causation rather than only crash data are extensively investigated in the current road safety research. Safety performance indicators (SPIs), which are causally related to the number of crashes or to the injury consequences of a crash, are rapidly developed and increasingly used. To measure the multi-dimensional concept of road safety which cannot be captured by a single indicator, the exploration of a composite road safety performance index is vital for rational decision-making about road safety. In doing so, a proper decision support system is required. In this study, we propose an improved hierarchical fuzzy TOPSIS model to combine the multilayer SPIs into one overall index by incorporating experts' knowledge. Using the number of road fatalities per million inhabitants as a relevant reference, the proposed model provides with a promising intelligent decision support system to evaluate the road safety performance for a case study of a given set of European countries. It effectively handles experts' linguistic expressions and takes the layered hierarchy of the indicators into account. The comparison results with those from the original hierarchical fuzzy TOPSIS model further verify the robustness of the proposed model, and imply the feasibility of applying this model to a great number of performance evaluation and decision making activities in other wide ranging fields as well.

1. Introduction

Transport system, as one of the most fast growing sectors, is expected to experience an accelerated expansion in the next decades. However, rapid growth of traffic volume, especially the motorized road mobility, has also resulted in continuously increasing safety problems. Worldwide, an estimated 1.2 million people are killed in road crashes each year, and as many as 50 million more are injured [1]. It not only imposes huge economic costs representing between 1% and 3% of GDP in most countries, but also causes great emotional and financial stress to the millions of families affected. More seriously, projections indicate that these figures will increase by about 65% over the next 20 years unless there is new commitment to prevention [1].

Given the high number of road casualties and the corresponding suffering and socio-economic costs, new measures are urgently needed to reduce this number and make progress in road safety. To this end, safety performance indicators (SPIs), which are causally related to the number of crashes or to the injury consequences of a crash (e.g., seat belt wearing rate), are rapidly developed and increasingly used, especially over the last decade (e.g., [2–4]). Knowledge on these indicators is valuable in understanding the processes that lead to crashes, determining the main risk factors, identifying the corresponding interventions, and monitoring the effectiveness of the safety actions that are taken.

Among various underlying risk factors of road safety, each risk factor (e.g., protective system) is possibly represented by several appropriate SPIs (e.g., seat belt wearing rate in front and rear seats, respectively) constituting a layered hierarchy. A simple comparison per indicator thus only shows a small piece of the road safety picture, which can be misleading since different countries may operate in different circumstances with different focal points. Consequently, to measure the multi-dimensional concept of road safety which cannot be captured by a single indicator, the exploration of a composite road safety performance index is attractive. The index presents the overall road safety picture by capturing a multitude of risk information in one index score, and offers advantages in terms of communication, benchmarking, and decision making [5,6].

Compared to other fields such as environment, economy, and society, the development of a composite index for road safety performance evaluation is relatively new. This is because the traditional research mainly focuses on the road safety final outcomes in terms of fatalities per head of population, vehicle fleet or other measures of exposure [7]. They are mainly limited to the "worst case scenario" in the unsafe operational conditions of traffic systems, and are insufficient in explaining more detailed aspects of crash causation and injury prevention. The progress of recent studies on the development of

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a composite road safety index includes both objective methods (e.g., principal component analysis, factor analysis, data envelopment analysis, neural networks and rough set theory) and subjective methods (e.g., analytical hierarchy process and budget allocation; see [5,8–11]). However, some limitations in practice need to be paid attention to. First, relatively small number of basic indicators was considered, for example, in [9] and [10], only one quantitative indicator was selected for each risk factor, which might be insufficient in reflecting the entire situation of the risk factors. While in [5] and [8], although one or several indicators were suggested for each factor, all of them were treated to be in the same layer, and the information on the layered hierarchy was ignored. Second, of all the methods mentioned above, those objective ones rely mostly on the quality of information about the indicators. In other words, they are usually used with the precondition that all the indicators are measurable and quantitative. If some of them are specified with either ordinal measures or the help of expert subjective judgments, these methods may not be applied directly. Moreover, concerning those subjective methods based on experts' opinions, only crisp values were used (see e.g., [11]). However, experts in practice prefer to give linguistic valued assessments rather than crisp value judgments, such as 'low', 'relatively low', 'high', and 'extremely high'. This phenomenon results from inability to explicitly state their preferences due to the fuzzy nature of the evaluation process. In this case, precise mathematical approaches are not enough to tackle such uncertain variables and derive a satisfactory solution. A new technique for road safety performance evaluation is thus required, which should be able to not only incorporate the knowledge from the experts but also reflect the information on the hierarchical structure of the indicators.

From a purely mathematical point of view, the aggregation convention used for composite indicators deals with the classical conflictual situation tackled in multi-criteria evaluation. Therefore, the use of a multi-criteria framework for composite indicators is relevant and desirable [12,13]. In this study, we investigate one of the well-known classical multi-criteria decision making (MCDM) methods, which is technique for order preference by similarity to ideal solution (TOPSIS) [14]. To deal with the aforementioned linguistic expression given by experts and the layered hierarchy of the indicators, which are common issues in today's performance evaluation and decision making activities but have seldom proper solutions, we design a new hierarchical fuzzy TOPSIS model. The new model can be treated as a natural extension of the classical TOPSIS, and a promising intelligent decision support system as well, because not only the knowledge from experts, but also the information on indicators themselves, i.e., their hierarchical structure, are taken into account simultaneously. In the application, the proposed model is used to evaluate the road safety performance for a set of European countries. The results are then compared with the ones from the original hierarchical fuzzy TOPSIS model (see Section 3) using the number of road fatalities per million inhabitants as a relevant point of reference.

The remaining of the paper is structured as follows. In Section 2, we describe the safety performance indicators used in this study and their hierarchical structure. In Section 3, we mainly focus on the development of an improved hierarchical fuzzy TOPSIS model based on a brief review of the classical TOPSIS, fuzzy TOPSIS and the original hierarchical fuzzy TOPSIS. In Section 4, we present the application of this improved model for road safety performance evaluation and provide the comparison results subsequently. Finally, we conclude the paper in Section 5.

2. Road safety performance indicators

Based on a review of safety policies in the European Union and its member states, several road safety risk factors were designated as central to road safety activities in Europe and were selected for the development of SPIs [2,6]. They are: alcohol and drugs, speed, protective systems, vehicle, roads, and trauma management. Moreover, each risk factor is measured by one or several performance indicators which are policy relevance, data availability and reliability. In this study, we construct a hierarchical structure of SPIs for road safety performance evaluation as in Fig. 1. More specifically, for alcohol and drugs, the percentage of drivers disrespecting the alcohol limit is the indicator (A1); the speed indicator is the percentage of drivers exceeding the speed limit in built-up areas (S1); the protective systems are represented by the seat belt wearing rate in front and rear seats, respectively (P1 and P2); the age distribution and the composition of the vehicle fleet are the two main aspects reflecting the vehicle performance, and each of them is represented by two different indicators, which are the share of passenger cars of maximum five years old (V1), the median age of the passenger car fleet (V2), and the share of motorcycles and heavy goods vehicles (HGV) in the vehicle fleet, respectively (V3 and V4); the motorways density (R1) and the share of motorways in total road length (R2) describe the roads domain, and for trauma management the health expenditure as share of the gross domestic product (GDP) is the selected indicator (T1).

From a wide range of international databases and recent publications of international working groups [15–18], values related to 2003 are obtained for the above 11 SPIs of 21 European countries being Austria (AT), Belgium (BE), Cyprus (CY), Czech Republic (CZ), Denmark (DK), Estonia (EE), Finland (FI), France (FR), Germany (DE), Greece (EL), Hungary (HU), Ireland (IE), Italy (IT), The Netherlands (NL), Poland (PL), Portugal (PT), Slovenia (SL), Spain (ES), Sweden (SE), Switzerland (CH), and United Kingdom (UK). In the following sections, we evaluate the road safety performance of each of these countries by combining these hierarchical SPIs into an overall index, and use the 2003 number of road fatalities per million inhabitants for these 21 countries as the reference point of the index results.

3. Methodology

3.1. Classical TOPSIS method

As one of the well-known classical MCDM methods, TOPSIS was first developed by Hwang and Yoon in 1981 [14]. It bases upon the concept that the chosen alternative should have the shortest distance from the positive-ideal solution (PIS) and the farthest distance from the negative-ideal solution (NIS), in which the PIS is formed as a composite of the best performance values exhibited by any alternative for each criterion, and the NIS is the composite of the worst performance values. Proximity to each of these performance poles is measured in the Euclidean sense (e.g., square root of the sum of the squared distances along each axis in the 'criterion space'), with optional weighting of each criterion. The construction process of this method is transparent, which makes it easily understood by the general public and can be used to support a desired policy. During the last three decades, a large number of research papers were published on TOPSIS theories and applications [19,20].

3.2. Fuzzy TOPSIS method

In most real world contexts, MCDM problems at tactical and strategic levels often involve fuzziness in their criteria and decision makers' judgments. For example, due to the uncertainty of human cognition and vague judgment, linguistic assessments rather than crisp numerical values are usually given by decision makers or experts. As a result, the application of the classical TOPSIS method may face serious practical problems. To deal with these qualitative,