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Assessing urban road safety through multidimensional indexes: Application of multicriteria decision making analysis to rank the Spanish provinces

Mercedes Castro-Nuño[a,*], M. Teresa Arévalo-Quijada[b]

[a] Applied Economics & Management Research Group, Universidad de Sevilla, Spain
[b] Department of Applied Economics III, Universidad de Sevilla, Spain

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ABSTRACT

The traditional unidimensional approach used in road safety research to assess road safety performance is based on achievements in outcomes, such as number of traffic accidents, fatalities and injuries. However, taking into account the complex nature of the road safety framework, a multidimensional approach may be advisable in which all agents involved in the decision making process are properly represented. This article provides two multidimensional safety indicators that combine a set of criteria related to economics, demographics and sustainable urban transportation to assess urban road safety performance in 50 Spanish provinces (NUTS-3 regions). Multicriteria Decision Making Analysis (MDMA) is used to determine the set of factors that should be prioritized to minimize urban traffic accidents and fatalities. Using an objective weighting method for the chosen criteria, the obtained results point to aspects associated with the degree of urban development being the most important factors in discriminating and ranking the alternatives (provinces). Consequently, elements such as higher urban population and services concentration, and more advanced both transport systems and roads network, are related to safer urban areas. The two proposed safety indexes can provide policymakers with a useful tool for decision making in the area of urban road safety by identifying key attributes that should be promoted in urban planning.

1. Introduction

According to the European Road Safety Observatory (ERSO, 2016), approximately 26,000 people died as a result of road accidents in the European Union (EU) in 2014. Of these, 9923 died in crashes on urban roads, equivalent to 38% of all road accident fatalities in the same year. This situation could escalate in coming years, bearing in mind that over 50% of the current world population lives in cities and that United Nations forecasts predict a 75% increase in the urban population by 2050 (see http://www.un.org/es/development/desa/news/population/world-urbanization-prospects-2014.html).

The absence of literature on the local consideration of urban traffic accidents is particularly relevant in the case of Spain, where previous studies exploring the issue on the territorial scale (Albalate et al., 2013; Gómez-Barroso et al., 2015; Rivas-Ruiz et al., 2007; Úbeda et al., 2016; Tolón-Becerra et al., 2009, 2013) do not consider accident impact in the urban area but analyze interurban road accidents. As such, the few studies that address the problem in urban areas focus either on the issue nationwide (García-Ferrer et al., 2007), or on specific cities and provinces (Albalate and Fernández-Villadangos, 2010; Cirera et al., 2001; de Oña et al., 2011, 2013; García-Altés and Pérez, 2007; Gotsens et al., 2011; Kanaan et al., 2009; Melchor et al., 2015; Nolasco et al., 2009; Prat et al., 2015).

With the aim of closing this gap in the research in the field, the purpose of the present article is to use Multicriteria Analysis to develop two multidimensional indexes combining factors that influence urban road safety in order to rank Spanish provinces (NUTS-3 regions according to the European Commission's territorial statistical classification) for the year 2013. Both indexes may improve upon the traditional unidimensional approach applied in road safety research, in which road safety performance comparisons are made based on achievements in outcomes, such as numbers of accidents, fatalities and injuries.

A review of the road safety literature shows that, according to authors such as Chen et al. (2016) and Khorasani et al. (2013), indexes and indicators are usually used to assess the efficiency of implemented road safety policies, due to the logical deficiencies of the traditional focus, based solely on an analysis of trends in numbers of accidents, fatalities and injuries. As Wegman et al. (2008) note, road safety indicators detect the influence of the conditions surrounding the execution of road safety by measuring the impact of the various interventions

* Corresponding author. Applied Economics & Management Research Group, Universidad de Sevilla, Avda. Ramón y Cajal, 1, 41018 Seville, Spain.
E-mail addresses: mercas@us.es (M. Castro-Nuño), arevalo@us.es (M.T. Arévalo-Quijada).

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made; and, as also stated by Chen et al. (2016), this enables comparisons to be made between different geographic areas (countries, regions, municipalities).

These road safety indicators are normally based on the aggregation of different criteria or points of view (quantitative and/or qualitative) that address different dimensions of the issue (Chen et al., 2015). One of the most recent aggregation methods applied in the field of road safety is based on Multicriteria Decision Making Analysis (MDMA), and this is the technique used in the present article.

General MDMA applications in transportation infrastructure management include studies such as Castillo-Manzano et al. (2009) and Deluka-Tibljaš et al. (2013). Precedents using this methodology for interventions in the specific area of road safety include studies that: apply the technique to decision making in optimal road design to improve safety on certain sections of road (Fancello et al., 2015; Sarrazin and De Smet, 2015); assess the implementation of specific road safety strategies, such as smart speed systems (Agusdinata et al., 2009); select the best locations for pedestrian crossings (Šimunović et al., 2010); carry out systematic reviews in which road safety criteria are included in the broad objective of sustainable transport (e.g., Mardani et al., 2015); prioritize transportation systems for heavy vehicle operation, including safety, productivity and environmental issues (Yang and Regan, 2013); and, from a broader perspective, plan national road safety policy in combination with a cost-benefit analysis (Gühnemann et al., 2012).

Moreover, recent research applies MDMA to formulate road safety indicators worldwide. For example, Abdullah and Zamri (2010) for the case of Malaysia; Campos et al. (2009) for Brazil; Haghighat (2011) and Mirmohammadi et al. (2013) for Iran; and, more broadly, Chen et al. (2016) and Khorasani et al. (2013) for EU countries.

The synthetic indexes proposed in this article could therefore provide a decision framework to advise urban road safety management. In the Public Health and Transportation fields, and more specifically in the Road Safety policy context, decision makers make complex decisions regarding the use of public funds in a framework that prioritizes a limited number of options within a constrained budget. In this context, some scholars regard an approach like MDMA as valuable tool for improving the policy process (e.g., Macharis et al., 2010), as it enables a specific goal to be achieved through a choice of alternatives that takes into account a number of different criteria and stakeholder opinions.

The article is organized as follows: first, following this introduction, the MDMA theoretical framework is described, detailing the specific application made in the present study. The obtained results are then set out, followed by the main conclusions drawn from their analysis.

2. Methodological framework: MDMA application

According to authors such as Vincke (1992), MDMA combines the different dimensions (economic, social, environmental, and technical) of a decision problem faced by a private or public agent and offers an integrated study that is close to reality. Many researchers have recognized the need to take into account the various objectives or criteria in the different aspects of a decision process, formulating the problem in a multicriteria framework under conditions of certainty. They apply outranking models directly to partial preference functions that are assumed to be preassigned for each criterion (Brans et al., 1986), using different techniques, as has been done in the current paper.

It is also worth noting that other relevant approaches to modeling uncertainty conditions exist that provide solutions to multicriteria problems in a dynamic framework (for example, through Approximate Dynamic Programming or ADP, where numerous innovative research studies have emerged in the field of transportation, e.g., Feighan et al., 1988; Guerrero et al., 2013; Medury and Madanat, 2013; Ouyang and Madanat, 2004; Yin et al., 2009).

2.1. The Promethee-GAIA method

Of all existing multiple decision methods for evaluating and ranking different alternatives, the PROMETHEE (*Preference Ranking Organization Method for Enrichment Evaluation*) method has been chosen for this article as, in the opinion of Al-Shemmeri et al. (1997) and Brans and Mareschal (2005), it is the tool best suited to solve these problems due to its simple results, the fact that it is easily understood by decision makers, its use of parameters that translate into economics, and its elimination of scale effects among the different alternatives.

$g_1(a), \dots g_k(a)$ are the criteria to be evaluated (described in the following section), and A is a set of n possible alternatives (represented by the 50 Spanish provinces (or NUTS-3 regions, according to the Eurostat territorial classification), excluding Ceuta and Melilla, as their small size could distort the results).

Preferences are established by weighting the considered criteria by assigning them relative importance. Higher weights are given to relatively more important criteria, and lower weights to those that are less important. To be specific, *weights* w_j are defined for criteria g_j, whereby:

$$\sum_{j=1}^{k} w_j = 1; \quad w_j > 0 \; j = 1, \dots, k \tag{1}$$

Thus, so-called *outranking flows* are obtained for each alternative (see Brans et al., 1986; Brans and Mareschal, 2005):

- the positive flow (φ^+) represents each alternative's power of dominance, i.e., its dominant nature over the remaining *n-1*.
- the negative flow (φ^-) expresses an alternative's weakness, the degree to which the remaining alternatives *n-1* are preferred to this alternative.

These flows give a *partial ranking* (PROMETHEE I) of the alternatives depending on their entering and leaving flows, and a *complete ranking* (PROMETHEE II) by considering the net flow, which is the difference between the two previous flows; thus, for alternative a, net flow would be given by the difference between the positive flow (φ^+) and the negative flow (φ^-).

The procedure applied to obtain these flows determines an aggregated preference index $\pi(a, b)$ for each pair of alternatives in all the considered criteria and indicates the degree of total preference for alternative a over alternative b, as in the following expression (2):

$$\pi(a, b) = \sum_{j=1}^{k} w_j P_j(a, b) \tag{2}$$

A particular preference function P_j is defined for each criterion g_j to take into account the decision maker's preference structure and indicate the degree of preference for alternative a over alternative b in criterion g_j, given by the difference between the respective evaluations for this specific criterion:

$$d_j(a, b) = g_j(a) - g_j(b) \tag{3}$$

Modeling the decision maker's preference structure is done by linking a pseudo criterion P_j to each criterion g_j, so that:

$$P_j(a, b) = P_j(d_j(a, b)) \quad \forall\, a, b \in A, \quad j = 1,2, \dots, k \tag{4}$$

with $0 \le P_j(a, b) \le 1 \quad \forall\, a, b \in A, \quad \forall\, j = 1, \dots, k$.

Function P_j indicates the degree of preference for alternative a over alternative b and depends on the deviation d_j that exists between evaluations of these alternatives for criterion g_j. The (g_j, P_j) pair is referred to as the *generalized criterion*.

This method also provides a powerful qualitative tool to complement these rankings, the GAIA (*Geometrical Analysis for Interactive Aid*) plane, which gives a 2D picture of the problem indicating the position of the alternatives (in the form of dots on the plane) with respect to the