ASSESSING URBAN ROAD SAFETY WITH MULTIDIMENSIONAL INDEXES: APPLICATION OF MULTICRITERIA DECISION MAKING ANALYSIS TO RANK SPANISH PROVINCES

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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 transport systems and road density, 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.

Keywords: Urban traffic safety, NUTS-3 regions, road safety index, ranking, Multiple Criteria Decision Making, PROMETHEE.

Research Highlights

- Urban road accidents must be addressed differently to accidents on rural roads.
- Multicriteria Analysis improves on the traditional unidimensional safety approach.
- Two multidimensional safety indexes are used to rank 50 Spanish NUTS-3 regions.
- The degree of urban development predominates in both of the road safety synthetic indexes.
- From a safety perspective, it is advisable to adopt a compact city model.

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, 9,923 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 & Fernández-Villadagos, 2010; Cirera et al., 2001; De Oña et al., 2011, 2013; García-Altés & 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 be 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 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 & 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 & 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 & 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 different aspects of a decision process over various objectives or criteria, formulating the problem in a multicriteria framework under conditions of certainty, applying outranking models directly to partial preference functions which are assumed to be preassigned for each criterion (Brans et al., 1986), using different techniques as we have chosen in the current paper.

Although it is worth noting the existence of other relevant approaches that provide solutions to multicriteria problems in a dynamic framework, modelling uncertainty conditions (for example, through Approximate Dynamic Programming or ADP, where a number of innovative researches has emerged in the field of transportation, e.g. Feighan et al., 1988; Guerrero et al., 2013; Medury & Madanat, 2013; Ouyang & 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 & 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.

$g_1(a),...g_k(a)$ 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:

$$\sum_{j=1}^{k} w_j = 1 \ \ ; \ w_j > 0 \ \ j = 1,...,k \qquad (1)$$

Thus, so-called *outranking flows* are obtained for each alternative (see Brans & Vincke, 1986; Brans & 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):

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

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:

$$d_j(a,b) = g_j(a) - g_j(b) \qquad (3)$$

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

$$P_j(a,b) = P_j\left(d_j(a,b)\right) \quad \forall a,b \in A,\ \ j = 1,2,\ldots,k \qquad (4)$$

with $0 \leq P_j(a,b) \leq 1 \quad \forall a,b \in A,\ \ \forall j = 1,\ldots,k$

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 criteria (vectors).

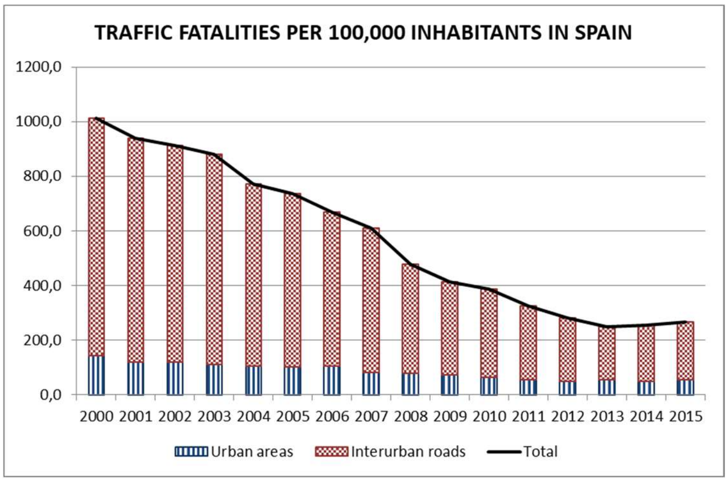
The software used in this article is Visual PROMETHEE Academic (available at http://www.promethee-gaia.net/software.html), based on the PROMETHEE and GAIA methods (Brans, 2015; Brans & De Smet, 2016; Brans et al., 1986).

2.2. Variables, alternatives, ranking criteria and weight assignment.

A detailed review of the prior literature on traffic accidents in urban areas was conducted to design the two synthetic indicators that enable the considered alternatives (50 Spanish provinces) to be ranked. The review identified a set of relevant variables that influence urban road safety and these were used to construct a database based on statistical information for 2013 taken from official sources.

The year 2013 has been chosen deliberately as it is the year when road traffic mortality rates in Spain experienced a trend change (see Figure 1). The series for interurban road accident rates also indicate a change in behavior (with a notable decrease) compared to urban areas (much more stable over time), suggesting that the latter environment would be a more relevant area for our research.

Figure 1. Evolution of traffic fatality rates in Spain



Source: authors with data from Directorate General of Traffic (DGT).

The set of 13 listing criteria is formed of the relevant considered variables and can be grouped into 7 categories of urban road safety factors. Tables 1 and 2 give the definitions of these criteria and their descriptive statistics, respectively.

Table 1. Variables considered (set of criteria)

Categories and Criteria		**Description**	**Source**
Road safety	**Urban traffic accidents per capita (Urban accident rate)**	No. of traffic accidents in urban areas / 100,000 inhabitants in Spanish NUTS-3 regions (provinces)	Spanish Directorate General of Traffic (DGT)
	Urban traffic fatalities per capita (Urban fatality rate)	No. of traffic fatalities in urban areas within 30 days of the accident (as per the Vienna convention) / 100,000 inhabitants in Spanish NUTS-3 regions (provinces)	Spanish Directorate General of Traffic (DGT)
Economic conditions	**GDP at market prices per capita (GDP PC)**	Gross Domestic Product per capita in thousands of Euros at market prices in Spanish NUTS-3 regions (provinces)	Spanish Regional Accounts
	GDP at market prices per capita: manufacturing activity (GDP PC manufacturing)	Gross Domestic Product per capita in thousands of Euros at secondary sector market prices in Spanish NUTS-3 regions (provinces)	Spanish Regional Accounts
	GDP at market prices per capita: construction activity (GDP PC construction)	Gross Domestic Product per capita in thousands of Euros at construction sector market prices in Spanish NUTS-3 regions (provinces)	Spanish Regional Accounts
Tourism activity	**No. tourists**	No. tourists recorded in Spanish NUTS-3 regions (provinces)	Hotel Occupancy Survey (from Spanish National

			Institute of Statistics, INE)
Demographic structure	**Age**	Mean age of provincial population in years	Spanish National Institute of Statistics, INE
	Population density	No. inhabitants per km^2 in Spanish NUTS-3 regions (provinces)	EUROSTAT
Healthcare system	**Hospital density**	No. public hospitals per km^2 in Spanish NUTS-3 regions (provinces)	National Hospital Source
Sustainability and urban transport	**No. smart cities**	No. towns and cities classified as Smart cities by the Spanish RECI in each of the Spanish provinces	Spanish Network of Smart Cities (Red Española de Ciudades Inteligentes-RECI)
	Urban train / subway	Existence of urban rail system and/or subway in each of the Spanish NUTS-3 regions (provinces)	Spanish Metropolitan Mobility Observatory
Mobility	**Motorization rate**	No. vehicles per 1,000 inhabitants (rate)	Spanish Directorate General of Traffic (DGT)
	Road network density	Km. totales de carretera / superficie en km^2 in each of the Spanish NUTS-3 regions (provinces)	Ministerio de Fomento and Spanish National Institute of Statistics (INE)

Table 2. Descriptive statistics for overall criteria considered

Criteria	Mean	Standard Deviation	Minimum	Maximum
Urban accident rate	76.93	52.35	10.51	242.68
Urban fatality rate	1.07	0.65	0.00	3.21
GDP PC	20.69	4.26	15.07	33.04
GDP PC manufacturing	3.57	1.78	0.57	8.26
GDP PC construction	1.22	0.47	0.74	4.00
No. tourists	168,376.22	222,0975.58	158,108.00	986,6485.00
Age	42.98	2.67	38.68	49.15
Population density	134.09	179.16	9.10	803.50
Hospital density	0.000064	0.000067	0.000058	0.0032
No. Smart cities	0.98	1.35	0.00	9.00
Urban train / Subway	0.22	0.41	0.00	1.00
Motorization rate	679.92	56.59	565.00	819.00
Road density	0.37	0.13	0.21	0.78

These 13 criteria have been combined to form two synthetic urban road safety indexes that provide two scenarios for analysis: one considering the urban traffic accident rate per capita (*Index 1*) and the other, the urban traffic fatality rate per capita (*Index II*).

Table 3 shows the composition of each index and specifies the preference function for each criterion (maximize or minimize) and the weights assigned in each index.

The criteria were classified into seven categories in accordance with the findings in the prior literature:

- Road safety: Following prior research (Chen et al., 2015, 2016, among others), two criteria have been considered: the urban traffic accident rate per 100,000 inhabitants; and the urban traffic fatality rate per 100,000 inhabitants recorded within 30 days of the accident, as per the system used by the Vienna Convention. Logically, the aim is for both of these criteria to be minimized in the multicriteria ranking.

- Economic conditions: Three economic activity-related criteria have been considered. First, GDP per capita at market prices, which has been maximized taking into account the existence of the so-called inverted U "*Kuznets road safety curve*": although the accident mortality rate might rise as a country's economy develops from a given income baseline, the trend decreases due to better infrastructure and healthcare, better developed prevention policies and greater user awareness (Bishai et al, 2006; Castillo-Manzano et al., 2014; Kopits & Cropper, 2005).

A criterion for GDP per capita at market prices for the secondary sector (manufacturing), and a criterion for the construction sector have been included in second and third position, respectively, in this category, as these two sectors of activity are linked to heavy vehicle traffic and so have implications for urban road safety. Following prior studies (e.g., Dablanc et al., 2013; Dong et al., 2014; Nuzzolo & Comi, 2014), the particular technical features of these vehicles and the difficulty that their maneuvering presents in urban areas suggest that a negative result should be expected for accident numbers; for this reason both criteria have been minimized when combined with the accident criterion.

However, these criteria have been maximized in the synthetic index for numbers of urban accident fatalities as, according to Castillo-Manzano et al. (2015, 2016), urban traffic slowing due to the circulation of these vehicles contributes to a decrease in the severity of urban traffic accidents.

- Tourism activity: A criterion connected with tourist movements recorded in the Spanish provinces has been considered on the basis of a link between tourism and urban road safety found in the prior literature. This criterion has been minimized as the evidence shows that there is a negative correlation between tourist activity and road safety (Rosselló & Sáenz de Miera, 2011; Sheng & Tsui, 2009) due to an apparent greater likelihood of tourists being involved in traffic accidents (Walker & Page, 2004), most likely on account of the higher risk inherent in journeys in an unknown environment (Page et al., 2001) coupled with the increased exposure that results from greater mobility and traffic congestion (Saénz-de-Miera & Rosselló, 2012).

- Demographic structure: According to earlier studies (Ewing et al., 2003, 2016; Yannis et al., 2015), the urban road accident rate seems to be negatively correlated with population dispersal (i.e., the greater the urban concentration, the lower the number of deaths per accident, as journey volume is considerably lower). A population density criterion has therefore been considered and maximized.

A further criterion has also been included related to the mean age of the population in each of the provinces. This criterion has been minimized, as evidence shows that despite younger drivers being more exposed to risk due to reckless driving, more driving errors and greater alcohol/drug DUI (Constantinou et al., 2011; Langford et al., 2006), it is the elderly who are frailer because of certain physical deficiencies (Li et al., 2003), and when the latter are involved in accidents, impacts in terms of morbidity and mortality are greater (Koppel et al., 2011).

- Healthcare system: The hospital density criterion has been maximized due to the beneficial influence that immediate post-accident medical attention has on road safety, as stated by Castillo-Manzano et al. (2013) and Sánchez-Mangas et al. (2010), among others.

- Sustainability and urban transport: Two variables are considered (Smart cities and Subway) as proxies to capture the influence of sustainable urban transport on urban road safety. Numerous studies consider smart traffic solutions (addressed by the concept of smart city) and infrastructure-related urban planning (such as subways and rail urban transport implementation) as indicators of urban sustainable livability from a perspective related to the model of the urban traffic system, traffic infrastructure, vehicle types and contribution to air pollution (see e.g., Albino et al., 2015; Debnath et al., 2014).

On the one hand, a criterion has been included related to the number of towns and cities in each of the Spanish provinces classified as Smart Cities by RECI (in Spanish: "Red Española de Ciudades Inteligentes" or Spanish Network of Smart Cities). We consider the concept of Smart City according to RECI's broad definition, which comprises: economic factors (such as competitiveness; innovation; entrepreneurship; productivity; and flexibility of the labor market); social and human capital (described by citizens' qualification and education levels); an adequate governance system (which comprises aspects of political participation; citizen services; and the functioning of the administration); a smart environment (described by attractive natural conditions and protection of resources); quality of living conditions (culture; health; and housing); and, also aspects of smart mobility (such as the availability of information and communication technologies; and sustainable, innovative and safe transportation systems).

This criterion is maximized, as there appears to be recent evidence that a smart urban transportation system integrated into the Smart City concept may help improve urban road safety (Agarwal et al., 2015; Krishnan & Balasubramanian, 2016; Zhuhadar et al., 2017).

A second criterion has also been included in this category related to the existence or nonexistence of a subway and/or light rail/tram system in urban settings in each of the Spanish provinces to capture the public urban transportation system's level of development and sustainability.

This criterion is also maximized, as previous studies (Kersys, 2015; Redman et al., 2013; Yannis et al., 2015) demonstrate that an inverse relationship exists with traffic accidents, since (as is logical) private vehicles not only contribute to hampering urban traffic, but also present worse road safety levels than public transportation.

- Mobility: A criterion has been considered relating to the motorization rate in each of the provinces. This criterion has been minimized, as higher motorization levels could imply greater exposure to traffic accidents (Albalate & Bel, 2012; Castillo-Manzano et al., 2013, 2015).

A criterion for Road Density has also addressed within this category and it has been maximizated because literature have early evidenced a key role to higher road network density to improve road safety (for example, see Castillo-Manzano et al., 2013; Soderlund & Zwi, 1995).

Table 3. Synthetic indexes for urban road safety in Spanish provinces

Indexes	Criteria	Preference	Weight (entropy %)
Index 1	Urban traffic accidents per capita	min.	7.88
	GDP PC	max.	0.49
	GDP PC manufacturing	min.	4.64
	GDP PC construction	min.	0.71
	No. tourists	min.	8.57
	Age	min.	0.04
	Population density	max.	14.54
	Hospital density	max.	10.09
	No. Smart cities	max.	15.35
	Urban train and subway	max.	36.13
	Motorization rate	min.	0.08
	Road density	max.	1.46
Index 2	Urban traffic fatalities per capita	min.	2.45
	GDP PC	max.	0.52
	GDP PC manufacturing	max.	3.18
	GDP PC construction	max.	1.42
	No. tourists	min.	9.18
	Age	min.	0.05
	Population density	max.	15.58
	Hospital density	max.	10.81
	No. Smart cities	max.	16.44

	Urban train and subway	max.	38.71
	Motorization rate	min.	0.09
	Road density	max.	1.57

With regard to the weighting or relative importance given to the criteria in the two indexes (see Table 3), it has to be recognized that although weight assignment might be the part of the methodology that is subjective (as weight determination depends on the decision maker's preference function), the technique used in the present article to compute weights is the Shannon & Weaver (1948) seminally developed *Entropy Method*, which enables *Nonsubjective Weight Determination*. This method was proposed by Zeleny (1982) as an objective technique for computing criteria weights. The assumption is that the relative importance of criterion j in a decision situation is directly related to the amount of information intrinsically generated about that criterion by the alternative set. Specifically, the more diverse the evaluations of the alternatives are (i.e., greater dispersion of alternative evaluations), the greater the importance that should be given to the criterion, due to its greater discriminatory power. As the objective is to measure a criterion's diversity, the Entropy Method is based on information theory as developed by Shannon & Weaver (1948).

Precedents can be found in the field of road safety assessment with MDMA that apply this technique to determine criteria weights, for example, in studies as Chen et al. (2015, 2016), Khorasani et al. (2013) and Safari et al. (2012).

The procedure consists of the following:

- All criteria should be given the same weighting (all max. or all min.).

- Evaluations should be normalized, i.e., for alternative i in criterion j, evaluation is expressed as (5):

$$a_{ij} = \frac{g_j(a_i)}{\sum_{i=1}^{n} g_j(a_i)}, \quad i = 1,..,n; j = 1,...,k \qquad (5)$$

- Entropy is computed for each criterion using the following expression (6):

$$E_j = -\frac{\sum_{i=1}^{n} a_{ij} Ln(a_{ij})}{Ln(n)} \qquad (6)$$

Whereby $0 \le E_j \le 1,\ j = 1,...,k$. The more equal or similar a criterion's evaluations a_{ij} are, the greater its entropy E_j is. This is the exact opposite of what would be wished to be the case if E_j was an approximate value of the criterion's weight w_j. Therefore the complement is used. This is the opposite measure, called the criterion's diversity D_j and defined as $D_j = 1 - E_j$.

- Lastly, diversities D_j are normalized and weights are obtained as follows (7):

$$w_j = \frac{D_j}{\sum_{j=1}^{k} D_j}, j = 1,...,k \quad (7)$$

3. Results

Two multidimensional indicators are obtained for each index with the application of this methodology. Listing the Spanish provinces according to these two indicators gives the following rankings and GAIA planes.

To be specific, Figures 2 and 4 show the partial ranking for each index based on entering and leaving preference flows, and complete ranking resulting from the net preference flow for each alternative or Spanish province. Note that the alternatives are linked to colored geometric symbols to indicate the Autonomous Community (i.e., Spanish regional government level) to which they belong.

Meanwhile, the groups in Figures 3 (3a and 3b) and 5 (5a and 5b) synthesize the results obtained for each index in GAIA planes from the perspective of the criteria and the alternatives, respectively. The positions of the criteria are represented using colored vectors, while the same colored geometric symbols as above are once more used to show the particular situations of the alternatives or provinces.

As for their interpretation, according to Brans (2015), Brans & De Smet (2016), Brans et al. (1986), alternatives considered to be good with respect to a given criterion should be turned in the same direction as said criterion's axis. Criteria which are represented by axes pointing in a similar direction indicate similar discriminatory powers over the alternatives, whereas if the axes face in opposite directions, they are in conflict with one another. The length of the axes representing the criteria should be taken into account, as they show each criterion's discriminatory power over the alternatives.

In addition, this descriptive plane also shows the vector k-dimensional represented as π, which is referred to as the *global decision axis* and represents the objective that results from weighting the criteria set once the criteria have been standardized.

It can be observed in the GAIA planes in Figures 3b and 5b that the vectors that could be related to a greater level of urban development (i.e., Hospital density; No. Smart cities; Urban train/Subway; Population density; and Motorization rate) overlap in both indexes, irrespective of the index's road safety criterion (accidents or fatalities) and the different weightings assigned using the entropy method. This indicates that they have the same discriminatory effect over the alternatives.

This dominating role that the urban development criteria categories play in ranking the Spanish provinces can also be seen in each index's *global decision axis* π (brighter red GAIA plane vectors; see Figures 3a and 5b), which is located in the same quadrant as the criteria set. This is evidence that, irrespective of whether we are considering the traffic accidents rate or traffic fatalities rate, these are the criteria that really hold sway in both of the multidimensional indexes and therefore determine the way that Spanish provinces are ranked, with provinces with better evaluations for these criteria in higher positions in the rankings.

To be more precise, the discriminatory power of the public urban transportation (Urban train and/or Subway) criterion stands out according to the entropy scores that it achieves in the two indexes, with weights approaching 40% in both composite indexes.

This leads us to state that urban road safety results are better in places where the population and services are concentrated, as it is the more developed areas, in urban terms (in relation to their economies; healthcare; mobility; better available public transportation; or which incorporate new technologies) that top the lists and where both fewer and less lethal traffic accidents occur. These results are in line with the findings stated by authors such as Castillo-Manzano et al. (2013), Ewing et al. (2003, 2016), Kersys (2015), Noland & Quddus (2004), Redman et al. (2013), Sukhai & Jones (2014), and Yannis et al. (2015).

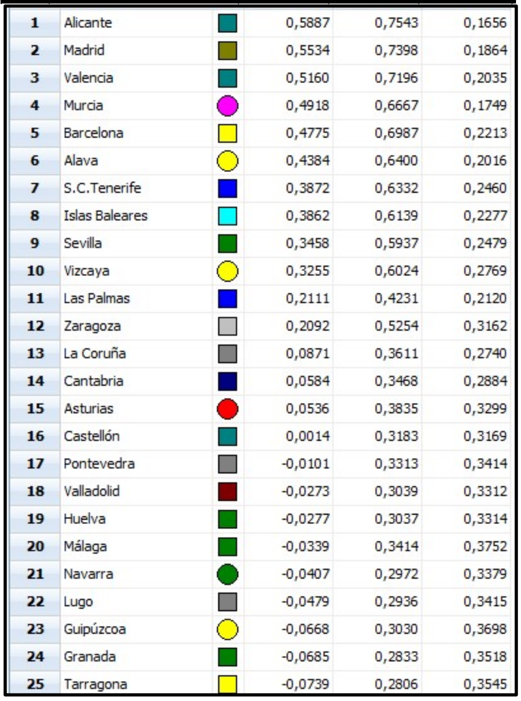
Given that in denser cities urban traffic congestion slows down driving speeds, when there are more advanced public transportation systems with a subway and/or urban train, and healthcare is nearer and faster, the city's categorization as a Smart city contributes to a reduction in the severest consequences of urban traffic accidents (as demonstrated by recent research by Agarwal et al., 2015; Krishnan & Balasubramanian, 2016; Zhuhadar et al., 2017).

When the relationship between road accident related criteria and the tourist activity criterion is considered in isolation for both indexes, the GAIA planes in Figures 3a and 4a) show that their respective vectors point in the same direction and are in very close proximity to each other in Index 1 (for traffic accident rates). Although they point in different directions in Index 2 (for traffic fatality rates). This suggests that provinces with less tourist activity present lower urban road accident rates, while provinces with more tourist activity present less urban traffic mortality rates.

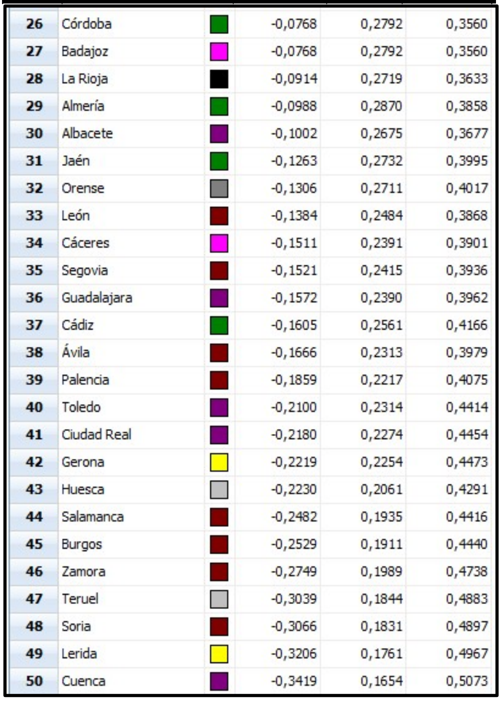
This result can be explained by the increase in urban traffic congestion caused by intense tourist activity. However, although this raises the risk of traffic accidents, these are less severe due to the traffic speed being slowed down. This enables evidence in previous studies, such as Rosselló & Sáenz de Miera (2011), Saénz-de-Miera & Rosselló (2012), Sheng & Tsui (2009), and Walker & Page (2004) to be extended to include the Spanish provinces.

The position of the vector of the demographic criterion for the mean age of the population (see Figures 3a and 5a) shows that it behaves differently in the two indexes: mean age and accidents per capita vectors appear in different direction, while mean age and fatalities per capita vectors have the same power of discrimination over the set of alternatives.

Figure 2. Promethee flow tables and ranking (R) of Spanish provinces according to Index 1 (Urban traffic accidents per capita)



R	Alternatives (provinces)		Phi	Phi$^+$	Phi$^-$
1	Alicante	🟦	0,5887	0,7543	0,1656
2	Madrid	🟫	0,5534	0,7398	0,1864
3	Valencia	🟦	0,5160	0,7196	0,2035
4	Murcia	🟣	0,4918	0,6667	0,1749
5	Barcelona	🟨	0,4775	0,6987	0,2213
6	Alava	🟡	0,4384	0,6400	0,2016
7	S.C.Tenerife	🟦	0,3872	0,6332	0,2460
8	Islas Baleares	🟦	0,3862	0,6139	0,2277
9	Sevilla	🟩	0,3458	0,5937	0,2479
10	Vizcaya	🟡	0,3255	0,6024	0,2769
11	Las Palmas	🟦	0,2111	0,4231	0,2120
12	Zaragoza	⬜	0,2092	0,5254	0,3162
13	La Coruña	⬛	0,0871	0,3611	0,2740
14	Cantabria	🟦	0,0584	0,3468	0,2884
15	Asturias	🔴	0,0536	0,3835	0,3299
16	Castellón	🟦	0,0014	0,3183	0,3169
17	Pontevedra	⬛	-0,0101	0,3313	0,3414
18	Valladolid	🟥	-0,0273	0,3039	0,3312
19	Huelva	🟩	-0,0277	0,3037	0,3314
20	Málaga	🟩	-0,0339	0,3414	0,3752
21	Navarra	🟢	-0,0407	0,2972	0,3379
22	Lugo	⬛	-0,0479	0,2936	0,3415
23	Guipúzcoa	🟡	-0,0668	0,3030	0,3698
24	Granada	🟩	-0,0685	0,2833	0,3518
25	Tarragona	🟨	-0,0739	0,2806	0,3545



R	Alternatives (provinces)		Phi	Phi$^+$	Phi$^-$
26	Córdoba	🟩	-0,0768	0,2792	0,3560
27	Badajoz	🟪	-0,0768	0,2792	0,3560
28	La Rioja	⬛	-0,0914	0,2719	0,3633
29	Almería	🟩	-0,0988	0,2870	0,3858
30	Albacete	🟪	-0,1002	0,2675	0,3677
31	Jaén	🟩	-0,1263	0,2732	0,3995
32	Orense	⬛	-0,1306	0,2711	0,4017
33	León	🟥	-0,1384	0,2484	0,3868
34	Cáceres	🟪	-0,1511	0,2391	0,3901
35	Segovia	🟥	-0,1521	0,2415	0,3936
36	Guadalajara	🟪	-0,1572	0,2390	0,3962
37	Cádiz	🟩	-0,1605	0,2561	0,4166
38	Ávila	🟥	-0,1666	0,2313	0,3979
39	Palencia	🟥	-0,1859	0,2217	0,4075
40	Toledo	🟪	-0,2100	0,2314	0,4414
41	Ciudad Real	🟪	-0,2180	0,2274	0,4454
42	Gerona	🟨	-0,2219	0,2254	0,4473
43	Huesca	⬜	-0,2230	0,2061	0,4291
44	Salamanca	🟥	-0,2482	0,1935	0,4416
45	Burgos	🟥	-0,2529	0,1911	0,4440
46	Zamora	🟥	-0,2749	0,1989	0,4738
47	Teruel	⬜	-0,3039	0,1844	0,4883
48	Soria	🟥	-0,3066	0,1831	0,4897
49	Lerida	🟨	-0,3206	0,1761	0,4967
50	Cuenca	🟪	-0,3419	0,1654	0,5073

Figure 3a. GAIA plane for criteria according to Index 1 (Urban traffic accidents per capita)

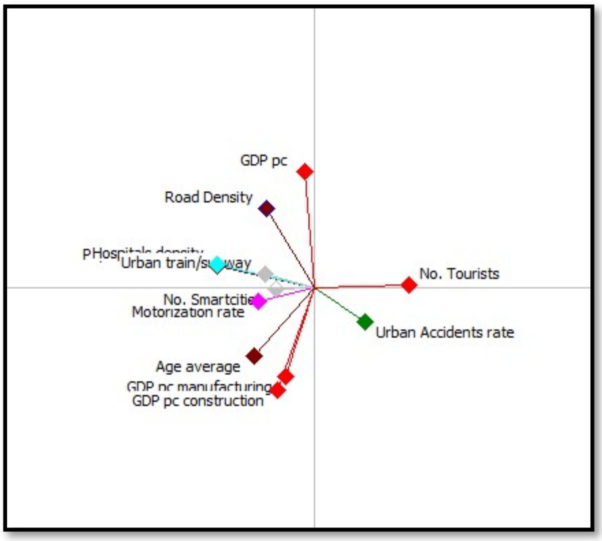


Figure 3b. GAIA plane for alternatives according to Index 1 (Urban traffic accidents per capita)

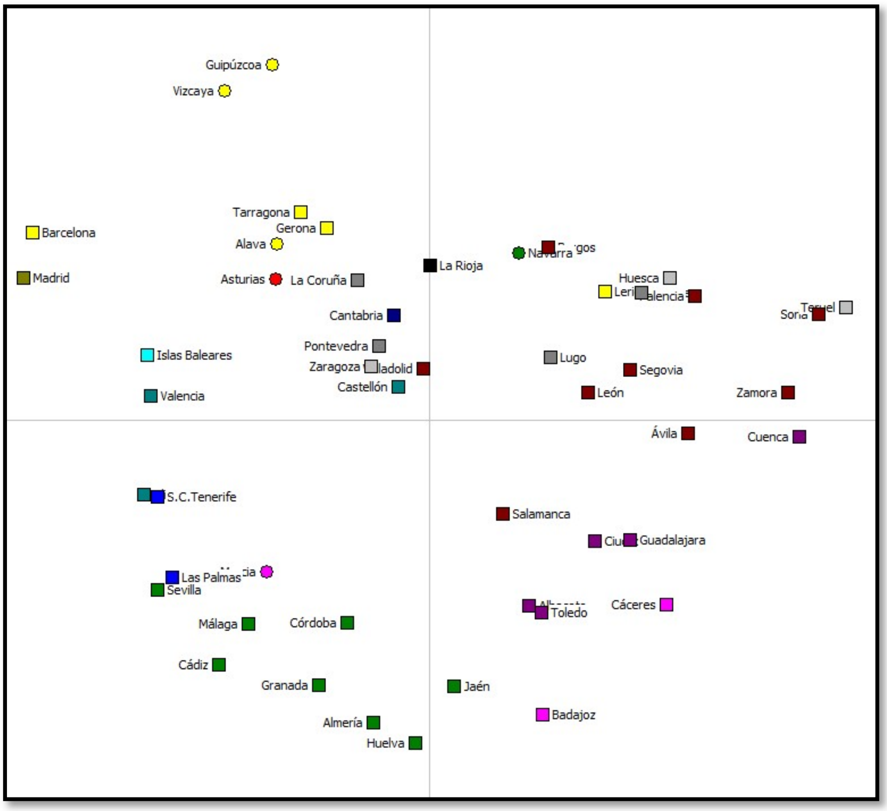


Figure 4. Promethee flow tables and ranking (R) of Spanish provinces according to Index 2 (Urban traffic fatalities per capita)

R	Alternatives (provinces)		Phi	Phi^{+}	Phi^{-}
1	Madrid	■	0,6298	0,7754	0,1456
2	Barcelona	■	0,6073	0,7608	0,1535
3	Valencia	■	0,5668	0,7422	0,1754
4	Alicante	■	0,5482	0,7312	0,1831
5	Alava	●	0,4901	0,6583	0,1681
6	Vizcaya	●	0,4481	0,6574	0,2093
7	Murcia	●	0,4146	0,6225	0,2079
8	Islas Baleares	■	0,4126	0,6215	0,2089
9	Sevilla	■	0,3667	0,5978	0,2311
10	S.C.Tenerife	■	0,3082	0,5882	0,2800
11	Zaragoza	■	0,2846	0,5570	0,2724
12	Asturias	●	0,1201	0,4058	0,2857
13	Guipúzcoa	●	0,0889	0,3687	0,2798
14	Las Palmas	■	0,0519	0,3293	0,2774
15	La Rioja	■	0,0488	0,3275	0,2787
16	Cantabria	■	0,0336	0,3194	0,2858
17	La Coruña	■	0,0292	0,3185	0,2893
18	Castellón	■	0,0288	0,3170	0,2882
19	Tarragona	■	0,0264	0,3175	0,2912
20	Valladolid	■	-0,0023	0,3022	0,3045
21	Navarra	●	-0,0341	0,2871	0,3212
22	Pontevedra	■	-0,0514	0,2978	0,3492
23	Lugo	■	-0,0696	0,2683	0,3379
24	Málaga	■	-0,1031	0,2967	0,3998
25	Albacete	■	-0,1149	0,2464	0,3613

R	Alternatives (provinces)		Phi	Phi^{+}	Phi^{-}
26	Córdoba	■	-0,1175	0,2451	0,3626
27	Granada	■	-0,1257	0,2397	0,3655
28	Gerona	■	-0,1257	0,2606	0,3864
29	Huelva	■	-0,1258	0,2417	0,3675
30	Orense	■	-0,1297	0,2584	0,3881
31	Palencia	■	-0,1318	0,2335	0,3653
32	Guadalajara	■	-0,1402	0,2343	0,3745
33	Segovia	■	-0,1432	0,2315	0,3747
34	Burgos	■	-0,1611	0,2238	0,3849
35	León	■	-0,1684	0,2184	0,3868
36	Huesca	■	-0,1725	0,2169	0,3893
37	Badajoz	■	-0,1782	0,2135	0,3917
38	Cádiz	■	-0,1858	0,2313	0,4172
39	Ávila	■	-0,1878	0,2060	0,3938
40	Jaén	■	-0,2144	0,2175	0,4319
41	Cáceres	■	-0,2287	0,1871	0,4158
42	Salamanca	■	-0,2353	0,1862	0,4215
43	Almería	■	-0,2393	0,2031	0,4424
44	Toledo	■	-0,2534	0,1973	0,4507
45	Ciudad Real	■	-0,2628	0,1921	0,4549
46	Lerida	■	-0,2725	0,1880	0,4605
47	Teruel	■	-0,2979	0,1755	0,4734
48	Soria	■	-0,3223	0,1628	0,4851
49	Zamora	■	-0,3246	0,1609	0,4856
50	Cuenca	■	-0,3842	0,1321	0,5164

Figure 5a. GAIA plane for criteria according to Index 2 (Urban traffic fatalities per capita)

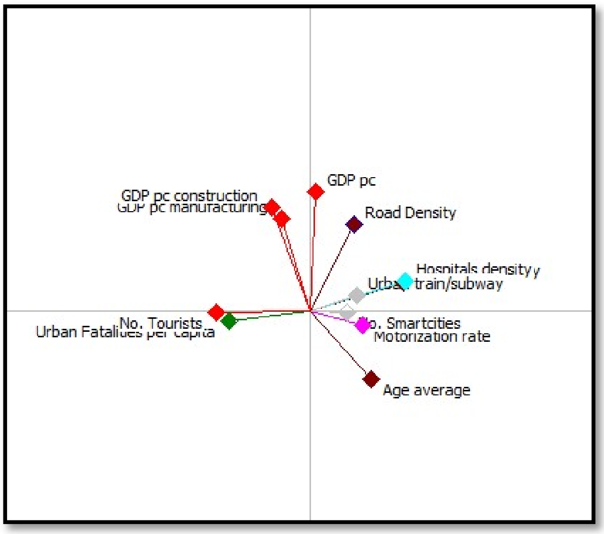
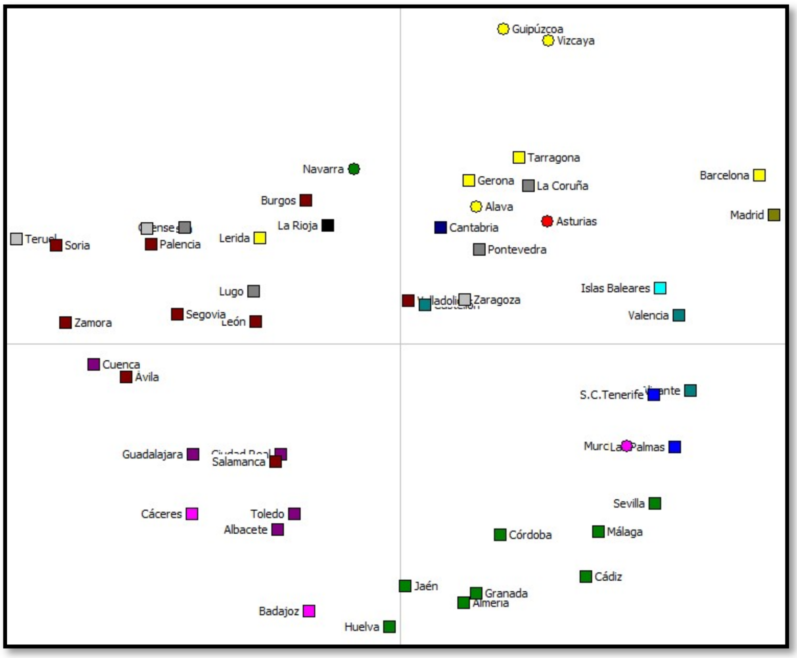


Figure 5b. GAIA plane for alternatives according to Index 2 (Urban traffic fatalities per capita)



Differences in the economic activity related criteria can be observed in the two indexes, as in Index 2 (see Figure 5a) the vectors that represent the three GDP PC criteria (total, manufacturing sector and construction sector) point in the same direction and are in quite close proximity to each other. This is indicative of the similar discriminatory powers that these three have over the alternatives. In contrast, in Index 1 (Figure 3a) they have conflicting discriminatory powers, as the total GDP PC criterion vector is pointing in the opposite direction to manufacturing sector and construction sector GDP PC. All this is in perfect line with what was stated in Section 2.2 when commenting on these criteria according to the prior literature.

The positions of the provinces (alternatives) in the GAIA planes for both indexes and the rankings show the Spanish provinces arranged by color and the Autonomous Communities of which they form part. Thus, provinces in the same Autonomous Community are located in the same quadrant of the plane. For example, Andalusian (represented by a green square) and Catalonian (yellow square) provinces are clustered in the same areas of the GAIA planes.

This result would to a certain extent be proof of an underlying geographic factor affecting the rankings and highlight the influence that different regional level management of the considered criteria (healthcare, public transportation, etc.) have on the rankings. It can also be observed that Northern and Central Spanish provinces are mostly located in the same quadrant as urban development related criteria in both indexes. This would explain the predominant positions of provinces with net positive flows in the respective rankings.

Lastly, Table 4 gives the results of a sensitivity analysis conducted to determine the robustness of the results to variations in the weights assigned to the criteria. As can be observed, given that a large number of criteria have been considered to construct the two composite indexes, the proposed solution seems to be sensitive to changes in the relative importance objectively assigned using the entropy method; this would indicate the high elasticity of Spanish urban road safety to changes in the variables considered.

Table 4. Sensitivity intervals of criteria weights

Indexes	Criteria	Weight (entropy %)	Min. (%)	Max. (%)
Index 1	Urban traffic accident rate	7.88	7.79	7.88
	GDP PC	0.49	0.48	0.58
	GDP PC manufacturing	4.64	4.51	4.65
	GDP PC construction	0.71	0.62	0.76
	No. tourists	8.57	8.50	8.58
	Age	0.04	0.02	0.08
	Population density	14.54	14.54	14.76
	Hospital density	10.09	10.09	10.36
	No. Smart cities	15.35	15.05	15.44
	Urban train and subway	36.13	28.08	36.25
	Motorization rate	0.08	0.08	0.25
	Road density	1.46	1.46	1.57
Index 2	Urban traffic fatalities rate	2.45	2.44	2.46
	GDP PC	0.52	0.51	0.52
	GDP PC manufacturing	3.18	3.17	3.18
	GDP PC construction	1.42	1.41	1.42
	No. tourists	9.18	9.14	9.20
	Age	0.05	0.00	0.09
	Population density	15.58	15.56	15.59
	Hospital density	10.81	10.80	10.82
	No. Smart cities	16.44	16.41	16.45
	Urban train and subway	38.71	26.93	100.00
	Motorization rate	0.09	0.09	0.10
	Road density	1.57	1.56	1.57

4. Concluding remarks.

The aim of the present work was to develop two synthetic indicators (considering, respectively, the rate of urban traffic accidents per capita and the rate of urban traffic fatalities per capita) based on Multicriteria Decision Analysis to build a decision making model for planning traffic safety interventions in urban settings. Both of the composite indexes were formed by aggregation, based on the objective weighting of several categories of criteria linked to variables that, according to the literature, are determinants of urban road safety. Both indexes were applied to list 50 Spanish provinces or NUTS-3 regions, enabling a ranking to be obtained that identifies the conditions that have the most influence on minimizing traffic accidents and their mortal consequences in urban settings.

Regarding this paper's contributions: First, this analysis shows how the proposed synthetic indexes could contribute to managing urban road safety compared to the traditional approach focused almost exclusively on the computation of traffic safety outcomes, such as numbers of accidents, fatalities or injuries. Considering the differential characteristics of urban areas regarding road safety, it is necessary to develop specific monitoring and sub central actions integrated through a multidimensional approach in which all stakeholders involved in the decision making process are represented and a set of corresponding attributes properly identified. Each province has its own geographic, demographic, socioeconomic and mobility peculiarities; thus, in this context, a composite ranking method such as that developed in the current paper could be a valuable tool to support fund allocation decisions, providing a methodological guidance to improve transparency of the policy process.

Second, our findings give a predominant role to criteria related to the degree of urban development and place provinces with more advanced sustainable urban transportation systems and that ensure greater proximity to appropriate medical attention at the top of the ranking. These provinces record fewer urban road accidents and accidents with lower mortality rates. These criteria have greater discriminatory power over the alternatives, even greater than purely economic variables or factors relating to one of the main drivers of the regional Spanish economy, such as tourism.

It is true that local authorities and transportation policy makers may have no influence on regional disparities in economic, social or demographic factors. However, they can determine urban transportation planning and play a decisive role in reducing traffic accidents in ways other than by simply implementing traditional traffic law enforcement measures (e.g., rules on drinking and driving, helmet and seat-belt use, speed limits). Our findings particularly point to a positive link between urban concentration (higher population and required services density) and safer urban traffic, meaning that urban sprawl might be a risk factor. Consequently, from the perspective of road safety it would be advisable to encourage a model of urban organization based on the compact city, where the activities of working, leisure, health, education, and so on, are not spread out over greater distances and people do not have to invest long periods of time in their daily journeys.

Finally, and with regard to future research lines, it would be interesting to apply both synthetic indexes to a new set of alternatives or larger geographic areas (e.g., European countries, NUTS-2 regions, etc.), and conduct an even more dynamic analysis with various combinatorial criteria scenarios to test urban road safety performance, and thus contribute to closing the gap in the literature on this topic.

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