Evaluating actions to improve the safety of urban provincial roads: a hierarchical multi-attribute approach

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key words: road safety, urban provincial roads, multi-attribute analysis, Monte Carlo simulation

Abstract

This paper describes a multi-attribute analysis that, when considering a set of urban provincial roads which are important from a safety standpoint, supports the decision-maker in choosing which ones to focus on as a priority. The decision-making support model considers and summarises the main parameters required to establish the criticality of the situations under consideration from the point of view of road safety.

This model has some distinctive features when compared to those previously published in the literature: a) it follows an original and simplified procedure to calculate the weights attributed to the criteria – this is based on the approach proposed by Simos (1990) and refined by Figueira and Roy (2002); b) it improves the robustness of the rankings by using the Monte Carlo simulation on sets of weights determined by a panel of experts; c) it is easy for technicians to use.

The analyses performed on a case study have shown that the evaluations obtained using the model are consistent with real-world situations. Furthermore, the Monte Carlo simulations have confirmed the robustness of the rankings with respect to the variability of the evaluations provided by experts. The proposed method can be easily developed and/or modified in order to evaluate other types of road.

1. INTRODUCTION

Using limited financial resources as efficiently as possible is a primary objective for the public administration and involves considerable responsibility and effort of decision-makers, whether they belong to the public or private sector. To support these decision-making processes, various evaluation techniques have been developed. These should not be viewed as procedures that automatically identify the best choice. Instead, they aid the decision-maker in systematically analysing the various options, helping to guide him or her towards the most effective and efficient choice.

To help achieve this goal, various evaluation techniques have been developed that offer a scientific (and therefore objective) approach to the problem. These methodologies can initially be grouped according to the metric used in the evaluation: a) monetary approaches (cost-benefit and cost-effectiveness analysis) (Mishan and Quah, 2007) and b) non-monetary approaches (multi-criteria analysis – MCA) (Greco *et al.*, 2016; Belton and Stewart, 2002).

The limitations of monetary approaches become clear in situations where it is difficult to identify a sole objective for the decision, i.e. situations where it is necessary to simultaneously consider various and conflicting aspects of a choice[1]. In these cases, the MCA can be used.

The theory underpinning the MCA (Keeney and Raiffa, 1976) is the possibility of breaking down the complex decision-making procedure into basic criteria which, when viewed as a whole, provide an exhaustive summary of all the aspects that must be considered. Following this initial step, MCA applies analysis/synthesis procedures that can adequately represent both the multi-dimensional nature of the decision and the specific preferences of the decision-maker.

Among the multi-criteria approaches, multi-attribute analysis (MAA) stands out thanks to its versatility and its ability to provide both overview and synthesis (Roy, 1996; Hwang and Yoon, 1981). MAA supports the decision-maker when he or she has to consider various pre-defined alternatives characterised by different levels of performance with respect to the conflicting objectives of the choice. The various MAA methods allow the user to organise and summarise complex and varied information in order to find an efficient solution that synthesises the various needs of the decision-maker in a transparent manner.

In this document, we have adopted a multi-attribute approach that, when considering a given set of urban segments of provincial roads and are critical from a safety standpoint, supports the decision-maker in choosing which ones to focus on as a priority. The decision-making support model considers and summarises the main technical parameters required to establish the criticality of the roads from the road safety point of view. The evaluation model uses a tree structure similar to the Analytic Hierarchy Process (AHP; Saaty, 1980) but uses a different approach to evaluate the weights to be assigned to the parameters and attributes. The weights were estimated by a panel of road safety experts using the method proposed by Simos (1990) and refined by Figueira and Roy (2002). Finally, an in-depth analysis of the evaluation results was carried out using a Monte Carlo simulation on the weights expressed by the experts.

This article is divided into four sections. The second section illustrates the problem of road infrastructure safety and refers to the main contributions to the field that have used the MCA and MAA. The third describes the evaluation model, focusing on the weight estimation procedure. The fourth details the structure of the model as used to evaluate the criticality of urban provincial roads, with a particular focus on the analysis and evaluation of the parameters to be considered and their relative weights. The fifth explores the case study and the simulations. The article ends with some concluding remarks.

2. EVALUATING ROAD SAFETY

Evaluating works to improve road safety is a complex problem which is very topical and not easily solved. It has become a key issue in all EU countries, which are obliged to pursue the objectives and guidelines set by the European Commission in the road safety action plan for the period 2011-2020. This document set the goal of halving the total number of road deaths (EU COM, 2010).

In Italy, the programme of interventions is titled "Piano Nazionale della Sicurezza Stradale Orizzonte 2020" (National Road Safety Plan 2020, Ministry of Infrastructure and Transport, 2014). Based on the results achieved in recent years and the EU's recommendations, the document reiterates the goal of halving road deaths by 2020 compared to those recorded in 2010. To achieve this goal, it is necessary to improve the safety of road infrastructure (EU Target No. 3) with a particular focus on vulnerable users such as pedestrians, cyclists and motorcyclists (EU Target No. 7).

As part of the previous Third Implementation Programme of the National Road Safety Plan (Ministry of Infrastructure and Transport, 2002), the Friuli Venezia Giulia Region (FVGR) had already set itself the objective of making urban provincial roads safer (FVGR, 2008).

This decision took into account the ten-year analysis of the Regional Road Safety Plan (from 1994-2003) and the analysis of the ISTAT data for the three-year period from 2004-2006, which highlighted the elevated danger posed by urban provincial roads. The piece of data that best highlights the pressing need for action is the high mortality rate of accidents on urban provincial roads, which accounts for almost 20% of the total road deaths in the region (Figure 1); since urban provincial roads make

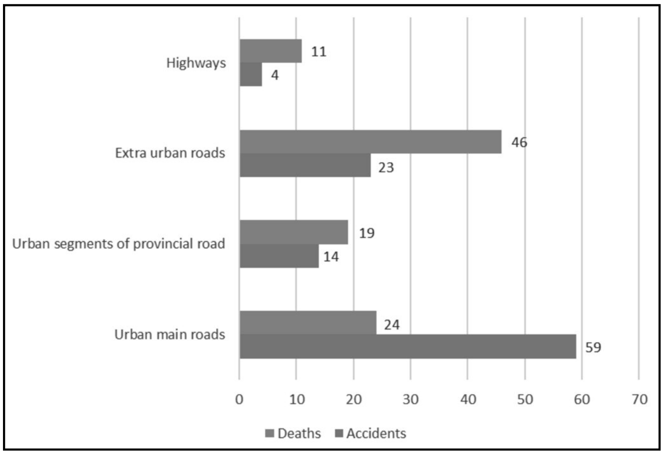

Figure 1 - *Location (%) of road accidents and deaths in FVG in the three-year period from 2004-2006 (Source: FVGR)*

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[1] In terms of the cost-benefit analysis, various methods have been developed to carry out monetary evaluations of aspects that are overlooked by the market (Pearce et al., 2004). However, implementing them is a rather arduous process and they are therefore ill-suited to decision-making problems that are limited in scope and have mainly technical content, such as the one in question.

Table 1 - *Number of accidents and deaths on urban main roads in the three-year period from 2004-2006 (regional and provincial roads) Source: FVGR*

	Province				Friuli Venezia Giulia Region
	Udine	Gorizia	Trieste	Pordenone	
Accidents	898	436	206	595	2.135
Deaths	46	4	8	26	84
Injuries	1,239	638	268	819	2.964
Social Cost (thousands €)	155,334	52,534	3,0880	96,533	335,281

Table 2 - *Number of accidents and deaths on urban segments of provincial roads in the three-year period from 2004-2006 (Source: FVGR)*

	Province				Friuli Venezia Giulia Region
	Udine	Gorizia	Trieste	Pordenone	
Accidents	326	90	89	25,7	762
Deaths	20	–	2	14	36
Injuries	422	136	115	356	1,029
Social Cost (thousands €)	58,947	10,010	11,253	45,723	125,933

up 4.4% of the entire network, we can deduce that the proportion of accidents on urban provincial roads resulting in deaths is over 5 times higher than the rest of the regional road network.

Tables 1 and 2 show the overall data relating to accidents on urban main roads in the FVGR, sorted by province, for the entire regional road network and provincial roads respectively.

The critical nature of urban main roads in general – and urban provincial roads in particular – is clearly demonstrated by the above data[2]. More recent data (ISTAT, 2017), while revealing a fall in the number of accidents and injuries, shows that the goal of halving the number of deaths caused by road accidents is still a long way off.

Various methods can be used to identify the segments of road that are most critical from a safety standpoint and consequently establish the order of priority for the action plan. Traditional methods aim to identify the segments of road with high accident rates, defined as "specified areas of the road network where the number of accidents is manifestly higher than other comparable areas". This approach, exemplified by Swiss standard 640009A (VSS, 2006), allows us to identify the most dangerous sections based on "distinctive accident indicators" that can be compared against pre-defined threshold values. These indicators can be refined using weighting coefficients adjusted to reflect the severity of each accident. While it is undoubtedly effective, this traditional approach to evaluating the safety of a road cannot take into account all the factors that contribute to defining how dangerous the road is. Accidents and injuries have a strong element of random chance to them, meaning that the relationship between the accidents observed and the intrinsic danger posed by a road is not always clear. The opportunity therefore arises to evaluate not only accidents but also other intrinsic and extrinsic characteristics of the roads in question, allowing us to consider all the aspects that define their potential criticality[3].

To summarise the various parameters which concur to define how critical a road is from a safety standpoint, we can use the MCA. The following is a chronological review of the main contributions that have used MCA/MAA procedures to evaluate critical issues and/or action priorities to improve road safety. It should be noted that the literature reviewed here often uses the term MCA to describe MAA approaches; we have decided to retain the names used by the authors.

Chowdhury *et al.*, (2000) describe a multi-objective methodology that identifies a set of efficient solutions to reduce accidents and their severity on motorways. The model developed: 1) identifies the critical factors of each

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[2] The tables list the data used to support the decisions made in the Third Implementation Programme of the National Road Safety Plan (FVGR, 2008).

[3] In this regard, the approach put forward in the Highway Safety Manual (AASTHO, 2010) published by the American Association of State Highway and Transportation Officials may be of interest. It provides an in-depth analysis of road safety from various points of view, such as studying the causes of accidents and countermeasures, evaluating interventions from a financial standpoint, deciding priorities and evaluating the effectiveness of interventions.

segment of motorway and the related solutions; 2) estimates the relationship between the accident rate and the cost of the solutions; and 3) identifies the best (efficient) solutions using a multi-objective analysis.

Kalamaras *et al.*, (2000) use the Analytic Hierarchy Process (AHP) to identify the best route for a motorway during the design stage. The attributes considered are: the impact on the environment, the safety of the section, construction time, construction and management costs and the profitability of the investment. The most important attributes were found to be the construction and management costs and the construction time.

Augeri *et al.*, (2011) present an interactive "dominance-based rough set approach" (DRSA) application which optimises the allocation of the resources available for motorway maintenance with the aim of improving safety. The analysis considers all infrastructure components (flooring, bridges, signs, guardrails, drains and hedges) and recommends the segments of motorway where it would be best to intervene.

Haghighat (2011) uses the Group Analytic Hierarchy Process (GAHP) to identify the criteria and sub-criteria useful for establishing the level of safety of roads in the province of Bushehr in Iran. He then uses the TOPSIS (Preference by Similarity to Ideal Solution) approach to obtain a ranking that identify the order of priority for interventions. The most important factor in determining how dangerous roads are is the rate of traffic regulation violations.

Cirovic and Pamucar (2013) apply fuzzy logic to identify railway crossings that require interventions to improve safety. They use an "Adaptive Neuro-Fuzzy Inference System" (ANFIS), trained by experts, to summarise all the factors that can influence the dangerousness of a railway crossing, particularly: the volume of rail traffic, the volume of road traffic, the presence of physical obstacles that limit visibility, signage, the presence of protective barriers, light and sound alarm systems, the condition of the road surface, and the angle of intersection between the road and the railway line.

Sarrazin and De Smet (2014), similarly to Kalamaras *et al.*, (2000), develop a theoretical MCA model for the assessment of road safety during the design phase. The authors consider two categories of attributes: road safety and environmental sustainability. Road safety takes into account how infrastructure is perceived, visibility, the protection of vulnerable users, the quality of the road surface, the presence of safety devices, the presence of intersections, the safety of road works and the presence of information and emergency services. The sustainability of the road is expressed in terms of greenhouse gas emissions, noise pollution, the level of service and the construction and maintenance costs. This evaluation uses the PROMETHEE II outranking procedure (Vincke, 1989).

De Bruker *et al.*, (2015) propose a two-stage MCA for the selection of intelligent transport systems with a particular focus on how road safety is perceived by users. In the first stage, the preferences of various categories of users are taken into account to identify the preferred solutions. In the second stage, the preferences of these various categories are summarised, with a greater emphasis placed on collective preferences. The evaluation is carried out with the aid of the AHP.

Similarly, Torok (2016) develops an MCA application to evaluate improvements in road safety thanks to the use of intelligent transport systems. In the first stage, the study uses the MCA to analyse the point of view of a panel of road safety experts regarding various intelligent transport systems. In the second stage of the research project, a cluster analysis is carried out to group the solutions according to their effectiveness.

Kanuganti *et al.*, (2017) put forward a study to identify roads where action should be taken as a priority to improve road safety. The features considered are the geometry of the road, the dimensions of the roadside and the quality of the road surface. To help identify the order of priority, the authors compare three different MAA techniques: Simple Additive Weight (SAW), Analytical Hierarchy Process (AHP) and Fuzzy AHP. Their analyses show that the three MAA methods lead to different choices.

3. THE MULTI-ATTRIBUTE EVALUATION MODEL

The decision-making problem addressed in this paper is the identification of urban roads managed by the province of Gorizia where action must be taken as a priority to reduce the dangerousness. With this in mind, the problem can be effectively tackled with a MAA procedure that can be expressed by the following formula:

$$\text{Order } (T_i) \text{ with respect to } I_i, \text{ where } I_i = f(A_{ij}) \qquad (1)$$

Where T_i are urban segments of provincial roads, I_i is the ordering criterion and A_j are the attributes with respect to which the choice will be made. In turn, these attributes depend on the technical characteristics of the road segments (x_{kj}).

To solve the problem, it is therefore necessary to specify the multi-attribute value function . MAA manuals (Hwang and Yoon, 1981; Vincke, 1989; Roy, 1996; Belton and Stewart, 2002; Greco *et al.*, 2016) offer various approaches for the construction of value functions able to summarise the many aspects of a decision-making problem.

To solve the problem addressed in this work, we chose a hierarchically structured linear model.

The structure of the model is represented by the (hierarchical) diagram shown in Figure 2. The technical parameters (x_k) are at the base of the pyramid, the intermediate level is represented by the attributes (A_j), and the synthetic indicator/is at the top.

The hierarchical model can be structured in various ways, with different levels of intermediate aggregation between the technical characteristics (x_i), the attributes (A_j) and the overall indicator (I).

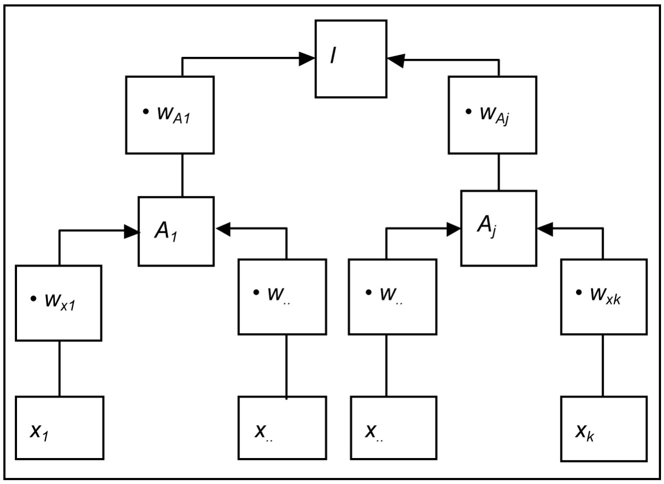

Figure 2 - *The hierarchical structure of the evaluation model*

The linear aggregation function uses weights (*w*) that can represent the contribution of a certain characteristic (*x*) in defining a certain attribute (*A*) and, subsequently, the weight of the attribute (*A*) on the state of the aggregate indicator (*I*).

The weight (w_x) assigned to a certain characteristic (*x*) is a scaling factor that allows it to be compared with the other characteristics in determining the state of the attribute (*A*). Likewise, the weight (w_A) assigned to a certain attribute (*A*) is a scaling factor that allows it to be compared with the other attributes in determining the state of the aggregate indicator (*I*).

The value function that estimates the state of the aggregate indicator can therefore be expressed as follows:

$$I = \sum_j w_{Aj} A_j \quad \textit{with} \quad A_j = \sum_k w_{xk} x_k \tag{2}$$

The procedure adopted in this paper is similar to Saaty's AHP in that it uses a hierarchical tree structure for the value function. However, it differs in the method used to estimate the weights. To overcome several criticality of the AHP, particularly the problem of "rank reversal" (Belton and Gear, 1983), the weights to be assigned to the technical parameters in order to estimate the attributes and to the attributes in order to estimate the aggregate indicator have been valuated using the "*revised Simos procedure*" suggested by Figueira and Roy (2002)[4], while a different and more intuitive weight calculation procedure has also been adopted.

The weight calculation procedure employs a "*bottom-up*" method that begins by estimating the attributes (A_j) and follows these steps:

1. for each attribute (A_j) of the hierarchy, all the technical parameters that define it (x_{jk}) are identified;
2. the parameters (x_{jk}) are ordered from the least important to the most important with respect to the contribution they make to defining the attribute (A_j) with the option of some being ranked equally; let ***r*** (r = 1,...r) be the number of positions (steps) in the ranking and c_r be the number of parameters on each step;
3. one or more "*blank cards*" are inserted into the ranking established in point 2). These represent the differences in significance between characteristics placed in consecutive positions; inserting a "*blank card*" means that, for the decision-maker, the difference in significance between two characteristics placed in consecutive positions in the ranking is double what it would be if there were no "*blank card*"; if we insert two "*blank cards*", the significance is therefore triple what it would be, and so on;
4. the value "one" is assigned to the parameter(s) placed on the first step, "two" to the second and so on until we reach the step with the most important parameter(s); the steps occupied by "*blank cards*" are included in this numbering process;
5. we delete the boxes containing "*blank cards*" from the numbered ranking; this way, the values assigned to each step (v_r) represent an initial, non-normalised judgement of the relative importance of the various parameters under consideration;
6. a ratio of importance (*z*) between the most important and the least important parameter is defined;
7. the weight w_r^z is calculated using linear interpolation in such a way as to obtain a ratio between the weight associated with the most important parameter and the least important one (equal to *z*):
$$w_r^z = v_r (z-1) / (v_{rmax} - v_{rmin}) + (v_{rmax} - z_{rmin}) / (v_{rmax} - v_{rmin})$$
8. for each step *r* of the ranking, the product of c_r and w_r^z is calculated, and these products are then added together $w_t^z = \Sigma_r w_r^z c_r$
9. the weight w_r^n is calculated, normalising w_r^z by w_t^z for each parameter belonging to each step *r* of the ranking: $w_r^n = w_r^z / w_t^z$

The following table illustrates the procedure for calculating weights, assuming four parameter x_r with a ratio (*z*) of relative importance of 3 between the most important and the least important one.

The improvement to the Simos method (1990) suggested by Figueira and Roy (2002) has several advantages, notably: a) it is based on an ranking defined directly by the decision-maker and is therefore more robust; b) it allows

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[4] Figueira and Roy (2002) showed that the relative amount of the weights obtained with the procedure proposed by Simos (1990) depended on the number of jointly-placed items present in the criteria ranking; they proposed a method to correct this skewed result.

Attribute	Position	c_r	v_r	w_r^z	$w_r^z \cdot c_r$	$w_r^n = w_r^z / w_t^z$	$w_r^n \cdot c_r$
x_1, x_2	1	2	1	1.00	2.00	0.136	0.273
Blank	2	1					
x_3	3	4	3	2.33	2.33	0.318	0.318
x_4	4	1	4	3.00	3.00	0.409	0.409
Total	10	8	8	w_t^z	7.33		1.000

the different weight of the criteria/attributes to be considered when making decisions by using the *"blank cards"*; c) thanks to the parameter z_j, weights can be assigned independently of the number of ex aequo. Moreover, with the simplified calculation suggested in this article, estimating the weights becomes fast and intuitive and can easily be carried out using a normal spreadsheet.

The procedure described above for estimating the attributes (A_j) is then repeated to obtain the weights in order to calculate the aggregate indicator (I) based on the attributes (A_j)[5].

This "*bottom-up*" approach was chosen because it begins by evaluating the most tangible basic parameters before moving on to consider increasingly synthetic and therefore abstract attributes. This means that users follow a self-learning process, making experts more aware of how weights are assigned.

The outcome of the procedure is a function that, given the parameters (x_k) of each road, calculates the synthetic indicator (I) that represents how critical it is and, implicitly, its ranking of priority of intervention.

Using a repeatable and objective analysis, this method allows us to identify the road segments that should be treated as high-priority, guaranteeing the effective and efficient use of the funds available.

4. MODEL FOR EVALUATING THE CRITICALITY OF URBAN PROVINCIAL ROADS

The procedure for evaluating the criticality of urban road segments described in the previous section was applied in various steps. First of all, we identified the characteristics of the urban roads (technical parameters) to be used in the analysis. Highway design and traffic safety engineering handbook (Lamm *et al.*, 1999) and the literature described in the second section allowed us to identify the most significant technical parameters. These were grouped into the following categories, each of which is summarised by an attribute:

a) *Alignment/Geometry of the road.*

a) *Exposure to risk.*

a) *Visual perception of the road.*

The procedures used to estimate the technical parameters and the corresponding evaluation methods are described below. The scores associated with the various parameter states are shown in Table 3.

4.1 Alignment/Geometry of the road

The geometric characteristics of the road are a very important aspect to consider when evaluating its criticality since they condition the behaviour of users with regard to speed and changes in vehicle trajectory. The characteristics under consideration are: the homogeneity of the cross-section, the horizontal and vertical alignment and the density of conflict points along the roadway segment.

4.1.1 Homogeneity of the cross-section

The cross-section of a road is composed of elements with various functional and geometric characteristics (lanes, shoulders, lateral moving spaces, etc.). Variations in the cross-section along a roadway segment alter how it is perceived by the user and have a significant influence on vehicle speed and trajectory. This increases the risk of accident, especially if the transitional sections are not suitably designed and signposted.

This parameter is defined qualitatively according to the following alternative classifications of the road cross-section:

- *not homogeneous*: the cross-section shows major variation within the roadway segment under consideration. For example, the road clearly narrows or widens enough to condition vehicle trajectory and speed;
- *somewhat homogeneous*: the cross-section displays small variations within the segment of road. These are limited to one side of the road or to elements outside the carriageway itself such as shoulder and therefore do not have a noticeable effect on vehicle trajectory;
- *homogeneous*: the elements that make up the cross-section do not display significant variation along the

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[5] In this paper a linear value function value was adopted and therefore any interactions between evaluation criteria were not taken into account. For a more in-depth look at this aspect, see Bottero *et al.*, (2015), Morano *et al.*, (2018) and Lombardi *et al.*, (2017)."

segment of road and their characteristics remain consistent throughout.

The road's degree of criticality is inversely proportional to the degree of homogeneity of its cross-section (Lamm *et al.*, 1999).

4.1.2 Curvature change rate

The overall curvature of the route was evaluated by means of the average Curvature Change Rate (CCR) of each segment of road. This index represents how "winding" the segment is. It is obtained from the ratio between the sum of the deviation angles of the road's curves in absolute terms and the length of the roadway segment.

$$CCR = \frac{\sum_i \omega_i}{\sum_i L_i}$$

Where:

$\omega_i = L_i/R_i$ angular deviation of the planimetric and transition curves present along the route

L_i = length of the geometric elements of the roadway segment of road in question.

Low values of CCR or curvature change (i.e. long tangent) cause the user to increase his or her speed, even where a 50 km/h speed limit is signposted. The higher the speed, the higher the risk of accidents with more serious consequences.

The intervals used to "quantify" the criticality of the road based on how winding it is follow a geometric progression with common ratio 2.

4.1.3 Density of conflict points

This parameter indicates the density of conflict points between traffic crossing the roadway segment under consideration and traffic on these segments themselves, measured in terms of the number of conflict points per kilometre. For the sake of simplicity, where two roads intersect, only the "crossing" points between two sets of traffic are considered, not those relating to merging manoeuvres. The calculation also needs to consider the number of entrances distributed along the entire length of the road section, whether they are public or private. The degree of criticality of the roadway segment is directly proportional to the density of conflict points thus calculated.

4.2 Exposure to risk

These parameters provide information on the likelihood of accidents occurring for users travelling on the segment of road in question. They depend on the size of the urban areas that the road travels through, the volume and make-up of the traffic involved and the accidents observed over the years. The parameters considered in this study are: the number of inhabitants in the municipality that the road travels through, the presence of vulnerable users on the carriageway, the accident rate and the injury index.

4.2.1 Population of the municipality

Larger built-up areas with more inhabitants and attractions entail greater movement of people and goods, increasing the risk of an accident and therefore the criticality of the urban roads that pass through them.

The municipalities crossed by urban segments of provincial roads have been divided into three sections here: less than 5,000 inhabitants, between 5,000 and 10,000 inhabitants, more than 10,000 inhabitants.

4.2.2 Vulnerable users

This parameter refers to the presence/absence of vulnerable users on the carriageway and is therefore based on the presence/absence of spaces reserved for pedestrians and cyclists (e.g. sidewalk and bicycle lane). The sharing of the carriageway by different categories of users is a source of critical issues caused by the different speeds of the various users. This parameter is represented by a binary variable.

4.2.3 Accident rate

The accident rate provides information on the number of accidents recorded on a roadway segment in relation to a period (years), the average daily traffic (ADT) and the length of the section. Swiss standard SN 640 009 (VSS, 2006) provides the following formula for calculating the accident rate of a section of road:

$$T_i = \frac{N_i \bullet 10^6}{TGM \bullet 365 \bullet T \bullet L_i}$$

Where:

N_i = number of accidents recorded in the roadway segment during the period *T*;

L_i = length of roadway segment in *km*;

TGM = average daily traffic during the period *T*;

T = period of time in years.

The value of the accident rate allows us to evaluate roadway segment with potentially high levels of accidents in relative terms. An evaluation in absolute terms is provided by the threshold values. The standard provides two different calculation methods depending on the data available: an approximate method and a detailed method. If no data on the volume of traffic is available, the approximate method allows the number of accidents *N* to be used as a characteristic indicator of the volume of accidents. The critical number of accidents, N_{crit}, is calculated using the following formula:

$$N_{crit} = N_m + k \bullet \sqrt{Nm} - \frac{1}{2}$$

Where:

N_m = average number of accidents in an interval, equal to the sum of all the accidents along the segment in question divided by the number of intervals;

k = statistical coefficient for a probability of error as a percentage (k = 1.645 for a probability of error of 5%).

4.2.4 Injury index

The injury index (R_F) is given by the number of injuries (F) in a given period of time *(t)* for every 1,000 accidents (I):

$$R_F = \frac{F}{I} \cdot 1000$$

This relationship can indicate the severity (or danger) of the accidents, although it is limited to subjects who were not fatally wounded.

4.3 Visual perception of the road

The parameters belonging to this category are those that influence the users' perception of the road and consequently influence their behaviour. The characteristics considered are: the road signs and markings, the density of the surrounding buildings and the area's land use.

4.3.1 Condition of signposting

This parameter indicates the condition of the road signs and markings for the road in question. These qualitative assessments have been assigned to the indicator, expressing the status of the signage as follows:

- *excellent*: the signs and markings have recently been maintained and are very clear, totally visible and fully complete;
- *good*: the signs and markings do not require maintenance, they are clear and clearly visible;
- *adequate*: the signs and markings do not require maintenance and are visible, although improvements could be made;
- *poor*: the signs and markings need maintenance, they are not fully visible, they are unclear if not lacking in places (markings), some elements are damaged or partially uprooted (signs);
- *very poor*: the signs and markings need maintenance, they are barely visible and sometimes incomplete (markings), they are badly damaged and partially missing (signs).

4.3.2 Land use of the surrounding area

The main land use of the surrounding area can influence not only the user's behaviour when driving (unobstructed views and reaction and perception times) but also the volume and make-up of traffic on the road at different times of the day. For this study, we have assumed that land has three possible uses: agricultural, residential, tertiary. The first category provides adequate unobstructed views and generates a limited volume of traffic. The second and third, meanwhile, generate incoming and outgoing flows that have a significant effect on the road in question.

4.3.3 Building density

The density of buildings in the surrounding of the road can affect the unobstructed views of drivers as well as their trajectories and operating speeds. Our qualitative description of this parameter is based on three possible levels: high, medium, low. In the first category, users have a restricted view. They have no difficulty in realising that they are in a built-up area and they moderate their speed accordingly. In the case of medium and low-density areas, users find it increasingly difficult to perceive the change in their environment. Moreover, the wider field of vision also causes them to maintain a high speed, increasing the criticality of the roadway segment.

4.4 Defining the overall criticality index

By synthesising the criteria described above, we can determine the overall criticality index of the road (Table 3). This is a risk indicator derived from an analysis of the road segment in question. This indicator is based on precise criteria that examine not only the current situation but also the road's "history" in terms of accidents.

In order to determine the overall criticality index, we need to define a set of weights to be associated to each evaluation criteria (technical parameters and attributes).

We called upon a panel of four road safety experts (identified using the letters A, B, C and D) to allocate the relative importance of the technical parameters in determining the attributes and of the attributes in determining the overall criticality index. The weights were estimated using the method described in section 3. After sharing the structure of the evaluation procedure and scoring system, the experts stated the importance to be attributed to each technical parameter when estimating the attributes (Tables 4 and 5) and the weight to be assigned to each attribute when estimating the criticality indicator (Tables 6 and 7).

5. APPLYING THE MODEL TO URBAN PROVINCIAL ROADS IN THE PROVINCE OF GORIZIA

The model described in section 3 and calibrated by evaluating the criticality of urban provincial roads in section 4 allows us to identify the roads where action needs to be taken as a matter of priority to improve road safety. The index value defined in (2), calculated for each roadway segment, is nothing more than the numerical

Table 3 - *The structure of the evaluation model and the scoring system*

	Attribute	Technical parameter	Parameter state	Score
Overall criticality index	Alignment/Geometry of the road	Homogeneity of cross-section	Not homogenous	10
			Somewhat homogenous	5
			Homogenous	0
		Curvature change rate	0 - 40	10
			40 - 80	7
			80 - 160	5
			160 - 320	3
			≥ 320	0
		Density of conflict points	>100	10
			60 - 100	7
			40 - 60	5
			20 - 40	3
			0 - 20	0
	Exposure to risk	Population of the municipality	> 10.000	10
			5,000 - 10,000	5
			< 5,000	1
		Vulnerable users on the carriageway	Present	10
			Absent	0
		Accident rate	$T_i > T_{crit}$	10
			$0 < Ti < T_{crit}$	5
			$T_i=0$	0
		Injury index	$R_f > 1,0$	10
			$0.5 < R_f < 1.0$	6
			$0 < R_f < 0.5$	2
			0	0
	Visual perception	Condition of signposting	Very poor	10
			Poor	7.5
			Adequate	5
			Good	2.5
			Excellent	0
		Land use of he surrounding area	Tertiary	10
			Residential	5
			Agricultural	0
		Building density	Low	10
			Medium	5
			High	0

expression of the criticality of these segments themselves.

As an example, the model has been applied to four urban segments of the SP.01 provincial road, which connects the centre of Fogliano Redipuglia and Pieris in the province of Gorizia. This road is approximately eight kilometres long and mostly flat. It crosses through the built-up areas of San Pier d'Isonzo and Turriaco and passes by industrial and agricultural areas as well as Ronchi dei Legionari Airport. Four segments of SP.01 have been identified; their characteristics are shown in the analysis matrix in Table 8.

Based on the scores associated with the state of the technical parameters of the segments of road under

Table 4 - *The weights assigned to the technical parameters by the experts*

Attribute	Technical parameter	Expert							
		A		B		C		D	
		Weight	Rank	Weight	Rank	Weight	Rank	Weight	Rank
Alignement/Geometry of the road	Homogeneity of cross-section	0,29	2	0,13	3	0,14	3	0,29	2
	Curvature change rate	0,14	3	0,50	1	0,29	2	0,14	3
	Density of conflict points	0,57	1	0,37	2	0,57	1	0,57	1
Exposure to risk	Accident rate	0,40	1	0,40	1	0,40	1	0,38	1
	Injury index	0,30	2	0,30	2	0,20	3	0,31	2
	Population of the municipality	0,10	4	0,10	4	0,07	4	0,08	4
	Vulnerable users	0,20	3	0,20	3	0,33	2	0,23	3
Visual perception of the road	Condition of signposting	0,50	1	0,52	1	0,15	3	0,34	2
	Land use of the surrounding area	0,30	2	0,30	2	0,48	1	0,44	1
	Building density	0,20	3	0,18	3	0,37	2	0,22	3

Table 5 - *The average, minimum and maximum weights assigned to the technical parameters*

Attribute	Technical parameter	Intervallo Weights interval					
		Minimum		Average		Maximum	
		Weight	Rank	Weight	Rank	Weight	Rank
Alignement/Geometry of the road	Homogeneity of cross-section	0,13	2	0,21	3	0,29	3
	Curvature change rate	0,14	1	0,27	2	0,50	3
	Density of conflict points	0,37	1	0,52	1	0,57	2
Exposure to risk	Accident rate	0,38	1	0,40	1	0,40	1
	Injury index	0,20	2	0,28	2	0,31	3
	Population of the municipality	0,07	4	0,08	4	0,10	4
	Vulnerable users	0,20	2	0,24	3	0,33	3
Visual perception of the road	Condition of signposting	0,15	1	0,38	1	0,52	3
	Land use of the surrounding area	0,30	1	0,38	1	0,48	2
	Building density	0,18	2	0,24	3	0,37	3

Table 6 - *The weights assigned to the attributes by the experts*

Attribute	Expert							
	A		B		C		D	
	Weight	Rank	Weight	Rank	Weight	Rank	Weight	Rank
Alignement/Geometry of the road	0,14	3	0,17	3	0,17	3	0,25	2
Exposure to risk	0,57	1	0,50	1	0,50	1	0,63	1
Visual perception of the road	0,29	2	0,33	2	0,33	2	0,12	3

Table 7 - *The average, minimum and maximum weights assigned to the attributes by the experts*

Attribute	Weights interval					
	Minimum		Average		Maximum	
	Weight	Rank	Weight	Rank	Weight	Rank
Alignement/Geometry of the road	0,14	2	0,18	3	0,25	3
Exposure to risk	0,50	1	0,55	1	0,63	1
Visual perception of the road	0,12	2	0,27	2	0,33	3

Table 8 - *The analysis matrix and the scores attributed to the technical parameters characterising the urban segments of*

Attribute	Technical parameter	Urban road segment							
		1A		1B		1C		1D	
		State	Score	State	Score	State	Score	State	Score
Alignement Geometry of the road	Homogeneity of cross-section	Homogeneus	0	Homogeneus	0	Somewhat Homogeneus	5	Homogeneus	0
	Cruvature change rate	0,00	10	43,86	7	20,26	0	0,00	10
	Density of conflict points	21,28	3	22,56	3	9,73	0	11,76	0
Exposure to risk	Accident rate	0,69	5	0,86	5	0,55	5	7,66	10
	Injury index	0,00	0	1,14	10	1,29	10	1,40	10
	Population of the municipality	5000	1	5.000-10.000	5	5.000	1	5.000-10.000	5
	Vulnerable users	Present	10	Present	10	Present	10	Present	10
Visual perception of the road	Condition of signposting	Good	2,5	Excellent	0	Good	2,5	Excellent	0
	Land use of the surrounding area	Residential	5	Residential	5	Residential	5	Agricultural	0
	Building density	Average	5	Low	10	Average	5	Low	10

Table 9 - *The weighted evaluation matrix for the technical parameters characterising the urban segments of SP.01*

Attribute	Technical parameter	Urban road segment			
		1A	1B	1C	1D
Alignement/Geometry of the road	Homogeneity of cross-section	–	–	1,05	–
	Cruvature change rate	2,70	1,89	–	2,70
	Density of conflict points	1,56	1,56	–	–
	Total	4,26	3,45	1,05	2,70
Exposure to risk	Accident rate	2,00	2,00	2,00	4,00
	Injury index	–	2,80	2,80	2,80
	Population of the municipality	0,08	0,40	0,08	0,40
	Vulnerable users	2,40	2,40	2,40	2,40
	Total	4,48	7,60	7,28	9,60
Visual perception of the road	Condition of signposting	0,95	–	0,95	–
	Land use of the surrounding area	1,90	1,90	–	
	Building density	1,20	2,40	1,20	2,40
	Total	4,05	4,30	2,15	2,40

Table 10 - *The weighted evaluation matrix for the attributes characterising the urban segments of SP.01*

Attribute	Urban road segment			
	1A	1B	1C	1D
Alignement/Geometry of the road	0,77	0,62	0,19	0,49
Exposure to risk	2,46	4,18	4,00	5,28
Visual perception of the road	1,09	1,16	1,09	0,65
Overall criticality index *(I)*	**4,32**	**5,96**	**5,29**	**6,41**

consideration, an initial "static" evaluation was carried out using the average weights shown in Table 5 and 7. A sensitivity analysis was then carried out on the ranking thus obtained, using a Monte Carlo simulation on the weights assigned to the technical parameters/attributes for which the experts' opinions differed.

Figure 3 - *The location of segment 1D*

5.1 Static analysis

The "static" evaluation of the criticality of the road segments was carried out by attributing the average weight stated by the experts to the parameters and attributes. Table 9 shows the weighted evaluation matrix for the technical parameters, obtained by multiplying the scores shown in the analysis matrix (Table 8) by the average weights shown in Table 5.

Table 10 shows the weighted evaluation matrix for the attributes, obtained by multiplying the total scores shown in the weighted evaluation matrix for the technical parameters (Table 9) by the average weights shown in Table 7.

The most critical segment of road was found to be 1D, followed by 1B, 1C and 1A. Segment 1D connects Fogliano Redipuglia to the north and San Canzian d'Isonzo to the south and extends from the periphery of the built-up area of San Canzian to the intersection with the SS 14 motorway (Figure 4).

Segment 1D is mainly critical due to the exposure to risk (accident and injury rates). As shown by the photos below, the presence of a rise at the start of this segment of road causes significant visibility problems for vehicles travelling along it. The absence of lanes reserved for vulnerable road users leads motorists to attempt to overtake by moving into the lane reserved for traffic coming in the opposite direction, even though they lack the visibility required to perform this manoeuvre.

An analysis of the geometry of the road and its cross-section leads to the following considerations:

- the environment surrounding the roadway is predominantly agricultural, with large open spaces on both sides of the road;
- the cross-section has no space for vulnerable users – pedestrians and cyclists are forced to share the carriageway with motor vehicles;
- since the land on both sides of the road is open and the road is almost straight when looking ahead of the section analysed, users often exceed the speed limit on this roadway segment.

5.2 Sensitivity analysis on the weights chosen by the experts

The sensitivity analysis carried out on the ranking obtained using the average weights arises from the fact

Figure 4 - *Segment 1D: intersection with the SS 14 motorway looking north (Fogliano Redipuglia) and south (San Canzian d'Isonzo)*

Figure 5 - *Segment 1D: the initial segment looking north (Fogliano Redipuglia) and south (San Canzian d'Isonzo)*

that the experts do not agree on the importance of certain parameters and/or attributes. It is therefore useful to estimate the effect of this range of opinions on the weight to be attributed to the criteria (technical parameters and attributes) and on the overall criticality index.

Using the position (rank) of the various parameters as a criterion for agreement among the experts, it is noticeable that, while a prevailing opinion (at least 3 out of 4 experts) is clear for some parameters, there is no agreement for others. In particular, two experts assign the lowest weight to the homogeneity of the cross-section while the other two rank it second. Moreover, the overall curvature of the route is ranked third by two experts, second by one and first by the other. The condition of the signpost is placed at the top of the list by two experts, while the others place it second. Finally, the land use of the surrounding area is considered the top priority by two experts, while the other two rank it second.

To evaluate the effect of these differing opinions on the weight to be attributed to the technical parameters and/or attributes, two simulations were performed using the Monte Carlo method[6] with 50,000 cycles. The first simulation (A) took into consideration a set of weights as follows:

1. for the parameters for which at least three experts agree on the ranking position, the average weight was used;
1. for the parameters "homogeneity of the cross-section", "overall curvature of the route" and "condition of the signage", triangular distributions were used based on the range of weights stated by the experts and a "most likely" equivalent to the average weight (see Table 5).

The results obtained using the simulation are summarised in the box plot graph in Figure 6.

The distribution of the criticality index of the four segments of road essentially confirms the ranking obtained using the static analysis, with segment 1D placed at the top of the ranking, albeit with a note of caution. The minimum value of the index for segment 1D (6.18) is lower than the maximum value for segment 1B (6.35). This means that the criticality index of segment 1D exceeds that of section 1B at a rate of less than 100% (95.2%).

The second simulation (B) took into consideration a set of weights that uses triangular distributions for all the technical parameters and attributes. These are based on

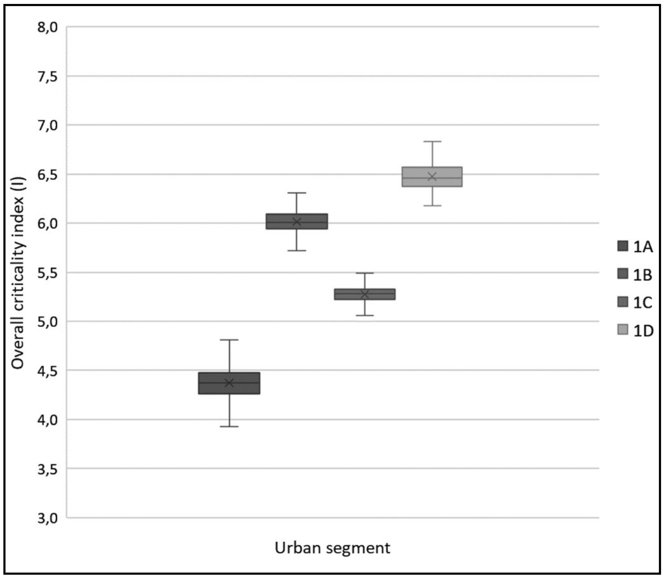

Figure 6 - *Criticality indices of the urban segments of SP.01 in Monte Carlo simulation A*

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[6] The Monte Carlo simulation (Vose, 1996; Ang and Tang, 2007) was developed in the first half of the last century to solve problems that were too complex to tackle analytically. It is based on the statistical analysis of a large number of outputs obtained from inputs with a certain distribution that are generated at random. In recent years, the Monte Carlo simulation has been widely used in situations where the MCA is applied to engineering (Galarza-Molina *et al.,* 2015; Wang *et al.,* 2015; Feizizadeh and Blaschke, 2014; Feizizadeh et al., 2014; Humphries Choptiany and Pelot, 2014; Tervonen *et al.*, 2009; Banuelas and Antony, 2004). In this work, it is used to evaluate the effect that

the range of weights stated by the experts and a "most likely" that is equivalent to the average weight (see Tables 5 and 7).

The results obtained with simulation B are summarised in the box plot graph in Figure 7.

The ranking obtained using this simulation is consistent with the one produced by simulation A, but is noticeably more fuzzy; there are significant overlaps between the criticality indices of the various road segments.

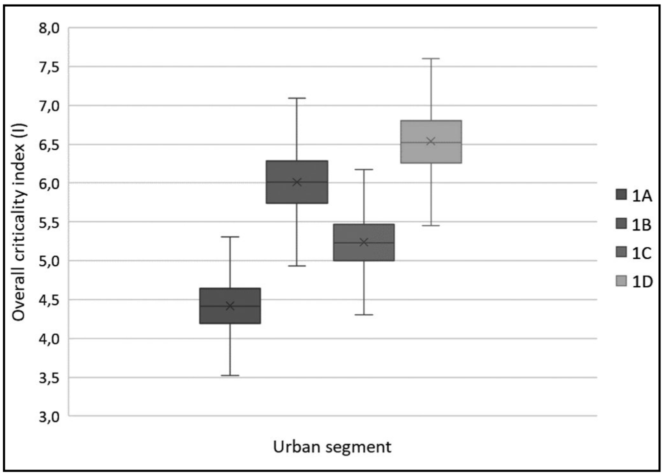

Figure 7 - *Criticality indices of the urban segments of SP.01 in Monte Carlo simulation B*

In order to evaluate the degree of robustness of the ranking that can be deduced by comparing the distributions, a test of the difference between the means of the criticality indices of the various road sections was carried out: all the averages were significantly different (Sig. 2-tailed 0.000) and therefore the ranking obtained can be considered robust with respect to the variability of the weights introduced in simulation B.

Finally, a pairwise comparison was carried out by calculating the frequency with which the value of the criticality index of a road section exceeds that of the alternative road segment (Table 11). This frequency, calculated based on the values simulated using the Monte Carlo method, represents the percentage of cases in which the criticality index of the road segment listed in the row exceeds the value of the road segment listed in the column: the higher this percentage, the more confident we can be in choosing the first over the second.

Table 11 - *Pairwise comparison matrix of the criticality level (%) of the segments*

		Urban segment		
		1A	1C	1B
Urban segment	1C	77.10		
	1B	97.50	70.3	
	1D	99.80	92.50	48.5

The overall analysis of the data listed in the table reveals the following:

1. The criticality of segment 1D is significantly higher than that of segments 1A and 1C.
2. The criticality of segment 1B is significantly higher than that of segments 1A and 1C.
3. The criticality of segment 1C is significantly higher than that of segment 1A.
4. The difference between the criticality levels of segments 1D and 1B is less clear.

In summary, Monte Carlo simulation B further confirms the ranking established by the static analysis and Monte Carlo simulation A, although it produces a slight difference between the criticality levels of segments 1D and 1B. The evaluation model therefore produces rankings that are rather robust with respect to the varied weights assigned by the experts.

6. CONCLUSIONS

The work carried out has allowed us to develop an analysis method capable of defining, for a given set of road segments, a ranking of priority for interventions to improve road safety. The method developed uses a hierarchical MAA procedure that produces an overall criticality index for each road segment with respect to various intrinsic and extrinsic parameters. This contribution has some distinctive features when compared to the existing literature on the evaluation of road safety improvement works.

1. it introduces a transparent procedure to compare the criticality of road segments that is also easy to implement;
2. it uses a simplified procedure to evaluate the weights to be associated with the technical parameters and attributes based on the approach proposed by Simos (1990) and later refined by Figueira and Roy (2002). The novel aspect of the procedure is that it normalises the scores associated with the Simos ranking using linear interpolation. This solves the problems highlighted by Figueira and Roy (2002) with a simpler and more intuitive calculation procedure.
3. it tests the stability of the rankings obtained with the evaluation model by using the Monte Carlo simulation on sets of weights determined by a panel of experts.

The solutions chosen when building this model allow the user to identify the most problematic roadway segments in terms of safety, with transparent and robust results. The analysis, evaluation and calculation procedures are totally transparent and repeatable, giving the user complete control over the procedure and allowing him/her to identify the reasons for a given ranking. This allows a case history of the road segments to be drawn up, helping to identify solutions.

The analyses performed on several urban segments of provincial roads in the province of Gorizia have demonstrated that the evaluations obtained using the model are consistent with real-world situations. Furthermore, the Monte Carlo simulations carried out based on the variability of the weights to be assigned to the evaluation parameters as expressed by the experts have confirmed the robustness of the ranking.

In conclusion, although created to address a specific problem, the method developed is a very flexible tool that can be adapted to different situations and objectives and that provides transparent, robust and repeatable results. Although the approach still has ample room for improvement, it can help to improve the effectiveness of road safety works and the allocation of financial resources by the public administration to increase the safety of a range of infrastructure.

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References

AASHTO - American Association of State Highway and Transportation Officials (2010) Highway Safety Manual.

Ang A. H-S., Tang W.H. (2007) *Probability Concepts in Engineering*, John Wiley & Sons Ltd, Chichester.

Augeri M.G., Colombrita R., Lo Certo A., Greco S., Matarazzo B., Slowinski R. (2011) *Dominance-Based Rough Set Approach to Budget Allocation in Highway Maintenance Activities,* Journal of Infrastructure Systems, 17(2).

Banuelas R., Antony J. (2004) *Modified analytic hierarchy process to incorporate uncertainty and managerial aspects,* International Journal of Production Research, 42(18).

Belton V., Gear T. (1993) *On a Shortcoming of Saaty's Method of Analytic Hierarchies,* Omega, 11(3).

Belton V., Stewart T. (2002) *Multiple Criteria Decision Analysis,* An Integrated Approach, Springer, Berlin.

Bottero M.C., Ferretti V., Figueira J.R., Greco S., Roy B. (2015) *Dealing with a multiple criteria environmental problem with interaction effects between criteria through an extension of the Electre III method,* European Journal of Operational Research, 245(3).

Chowdhury M.A., Garder N.J., Li D. (2000) *Multiobjective Methodology for Highway Safety Resource Allocation,* Journal of Infrastructure Systems, 6(4).

Cirovic G., Pamucar D. (2013) *Decision Support Model for Prioritizing Railway Crossing for Safety Improvements: Application of the Adaptive Neuro-Fuzzy System,* Expert Systems with Applications, 40(6).

EU COM (2010) *Towards a European road safety area:* policy orientations on road safety 2011-2020.

De Bruker K., Macharis C., Verbeke A. (2015) *Two-Stage Multi-Criteria Analysis and the Future of Intelligent Systems-Based Safety Innovation Projects*, IET Intelligent Transport Systems, 9(9).

Feizizadeh B., Blaschke T. (2014) *An uncertainty and sensitivity analysis approach for GIS-based multicriteria landslide susceptibility mapping,* International Journal of Geographical Information Science, 28(3).

Feizizadeh B., Jankowski P., Blaschke T. (2014) *A GIS based spatially-explicit sensitivity and uncertainty analysis approach for multi-criteria decision analysis,* Computers and Geosciences, 64.

Figueira J., Roy B. (2002) *Determining the Weights of Criteria in the ELECTRE Type Methods with a Revised Simos' Procedure,* European Journal of Operational Research, 139.

Galarza-Molina S.L., Torres A., Moura P., Lara-Borrero J. (2015) *CRIDE: A case study in multi-criteria analysis for decision-making support in rainwater harvesting,* International Journal of Information Technology and Decision Making, 14(1).

Greco S., Ehrgott M., Figueira J.R. (ed.) (2016) *Multiple Criteria Decision Analysis, State of the Art Surveys,* Springer, Berlin.

Haghighat F. (2011) *Application of a multi-criteria approach to road safety evaluation in the Bushehr province,* Iran, Promet - Traffic - Traffico, 23(5).

Humphries Choptiany J.M., Pelot R. (2014) *A Multicriteria Decision Analysis Model and Risk Assessment Framework for Carbon Capture and Storage*, Risk Analysis, 34(9).

Hwang C., Yoon, K. (1981) *Multiple Attribute Decision Making, Methods and Applications A State-of-the-Art Survey,* Springer, Berlin.

ISTAT (2017) *Incidenti Stradali in Friuli-Venezia Giulia, Anno 2016*, Focus Statistiche - ISTAT, Roma.

Kalamaras G.S., Brino L., Carrieri G., Pline C., Grasso P. (2000) *Application of Multicriteria Analysis to Select the Best Highway Alignment*, Tunneling and Underground Space Technology, 15(4).

Kanuganti S., Agarwala R., Dutta B., Bhanegaonkar P.N., Singh A.P., Sarkar A.K. (2017) *Road Safety Analysis Using Multicriteria Approach: A Case Study in India*, Transportation Research Procedia, 25.

Keeney R.L., Raiffa H. (1976) *Decisions with Multiple Objectives: Preferences and Value Trade-offs*, John Wiley & Sons.

Lamm R., Psarianos B., Mailander T. (1999) *Highway Design and Traffic Safety Engineering Handbook*, McGraw-Hill Companies Inc.

Lombardi P., Abastante F., Torabi Moghadam S.,Toniolo J. (2017) *Multicriteria Spatial Decision Support Systems for Future Urban Energy Retrofitting Scenarios*, Sustainability, 9(7).

Mishan E.J., Quah E. (2007) *Cost-Benefit Analysis (5th edition)*, Routledge. New York.

MIT - Ministero delle Infrastrutture e dei Trasporti (2002), *Piano Nazionale Sicurezza Stradale*, Azioni Prioritarie.

MIT - Ministero delle Infrastrutture e dei Trasporti (2014) *Piano Nazionale Sicurezza Stradale*, Orizzonte 2020.

Morano P., Tajani F., Locurcio M. *(2018) Multicriteria analysis and genetic algorithms for mass appraisals in the Italian property market*, International Journal of Housing Markets and Analysis, 11.

Pearce D., Mourato S., Atkinson G. (2004) *Recent Development in Environmental Cost-Benefit* Analysis, OECD.

RFVG - Direzione centrale mobilità, energia, e infrastrutture di trasporto (2008) *Terzo programma di attuazione del piano nazionale della sicurezza stradale PNSS*.

Roy B. (1996) *Multicriteria Methodology for Decision Aiding*, Springer, Berlin.

Saaty, T.L. (1980) *The Analytic Hierarchy Process*, McGraw-Hill Companies Inc.

Sarrazin R., De Smet Y. (2014) *Using Multicriteria Decision Analysis to Assess the Sustainable Safety Performance of Road Projects at the Design Stage, CoDe SMG - Technical Report Series*, Belgian Road Research Centre BRRC.

Simos J. (1990) *Evaluer l'impact sur l'environnement: Une approche originale par l'analyse multicritere et la negociation*, Presses Polytechniques et Universitaires Romandes, Lausanne.

Tervonen T., Figueira J.R., Lahdelma R., Dias J.A., Salminen P. (2009) *A stochastic method for robustness analysis in sorting problems*, European Journal of Operational Research, 192(1).

Torok A. (2016) *Statistical Analysis of Multi-criteria Assessment of Intelligent Traffic Systems for the Improvement of Road Safety*, Journal of Finance and Economics, 4(5).

Tzeng G., Huang J. (2011) *Multiple Attribute Decision Making, Methods and Application*, CRC Press, Taylor & Francis, Baton Rouge.

Vincke P. (1989) *L'aide multicritère à la décision, Statistiques et mathématiques appliquées*, Editions de l'Université Libre de Bruxelles, Brussels

Vose D. (1996) *Quantitative Risk Analysis: A Guide to Monte Carlo Simulation Modelling*, John Wiley & Sons Ltd, Chichester.

VSS (2006) *Accidents de la circulation; Localisation et classement des accidents (points noirs)*, Doc. Num. 640009A.

Wang H., Jiao W., Lahdelma R., Zhu C., Zou P. (2015) *Stochastic multicriteria acceptability analysis for evaluation of combined heat and power units*, Energies, 8(1).