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A decision support system for road safety analysis

Gianfranco Fancello [a,*], Michele Carta [a] and Paolo Fadda [a]

[a]*D.I.C.A.AR, Department of Civil and Environmental Engineering and Architecture, University of Cagliari,09123 Cagliari, Italy*

Abstract

The aim of this paper is to develop a procedure for supporting public administrations in planning safety interventions on the road network. Road safety conditions depend on several factors, represented by a variety of quantitative and qualitative data, including: number of traffic accidents, traffic flow, lane width, shoulder width, road curvature and grade, access-point density, road markings and road signs (Mooren et al. 2012; OECD, 2002). By analysing a set of given roads or different sections of the same road, each with specific safety conditions, this methodology allows to determine which sections require interventions to improve safe driving conditions. Specifically, the multicriteria analysis technique is used in decision-making processes to support the choice among different alternatives in complex problems (Fadda, 2002). Among the different multicriteria techniques available, the Concordance Analysis will be used here. This paper proposes a unique modelling tool that incorporates the different indicators to calculate safety conditions. The methodology has been applied to a real case study for evaluating road safety on sections of a motorway infrastructure.

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Keywords: multicriteria; concordance analysis; road safety conditions

1. Introduction

The management of funds to be allocated in safety interventions is one of the most important aspects of public administration. It is not only a question of the financial resources required but also the consequences of inadequate road maintenance, in terms of road accidents and/or above all damage to persons and property. However, it often (indeed almost always) happens that resources are insufficient to keep roads in good condition and up to required standards. Thus when planning safety interventions on the road network, public authorities are faced with the need

* Corresponding author.
E-mail address: fancello@unica.it

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to decide on which portions of the road network to intervene as a function of available resources. Clearly, when road segments exist with a high frequency of accidents involving casualties, the choice is obvious. In many cases, however, the selection process in not simple in so far as achieving road safety involves different variables concerning the infrastructure itself, traffic flows, surrounding environment, etc.

To ensure that this choice is as objective as possible and to actually reduce accident risk, a decision support system is required to assist public authorities in identifying those sections of road (and hence allocation of funds) where safety interventions should be carried out. This procedure should be able not only to account for all those variables that contribute to making the road dangerous, but also to establish intervention priority among different road sections.

In the scientific literature there are numerous papers focused on road safety and planning interventions but there is not a unique methodology to support the administrator of the road when it is necessary to optimize resources allocated to safety. Saaty (1995) applies the Analytic Hierarchy Process (AHP) to transportation planning with multiple criteria, Dell'Acqua (2011) presents a classification model of black spots in road networks using a decision support system (DSS) based on cluster analysis techniques. Coll et al. (2013), present a contribute to the ongoing research effort on the estimation of road safety composite index for identification and ranking of hotspots.

This paper presents a methodology for ranking the different alternatives by comparing them on the basis of different variables. In the specific case, a multicriteria technique called Concordance Analysis (Giuliano, 1985) is adopted. This technique is usually applied applied to choice problems but is used here for the first time for ranking purposes. In strictly analytic terms, the level of safety of a road infrastructure is a function of the characteristics of the users (c_u), of road geometry (c_g) and of traffic flow (c_f).

$$l_s = f(c_u, c_g, c_f) \tag{1}$$

Analysis of the component (c_u) is beyond the scope of this work. Of the traffic flow characteristics reported in the literature as having a major bearing on safety are the presence of heavy vehicles, traffic intensity and vehicle density (Martin J. L., 2002), while for road geometry, lane width, the presence of shoulders, road curvature and surface regularity (Karlaftis et. al., 2002) are the most significant.

$$g_k = f(c_u, c_g, c_f) \tag{2}$$

These conditions are expressed by objective functions that define the overall safety performance of a road infrastructure. When the road does not comply with adequate performance standards, then it becomes necessary to intervene to to ensure good safety conditions. The work to be carried out to achieve this is however subject to budget constraints. When available funds are not sufficient to cover all the safety interventions required, then the most critical road sections need to be identified. Here we propose a decision support model that defines a set A', a subset of all the elements comprised in the network $A = (a_1, a_2, a_3, \dots, a_n)$, containing those elements with the lowest level of safety l_s. The authorities of the road can use this analysis to identify the road segments with the worst safety conditions. Therefore available funds may be used to improve safety conditions of these elements.

2. Methodology

In this paper we use the multicriteria method called "Concordance Analysis", as described by Giuliano, G. (1985); this analysis is derived from Electre I method and uses the outranking relations based on both concordance and discordance analysis. This techniques addresses the "α " problematique whose objective is to identify the best alternative from among a finite number of competing alternatives. Roy (1996) provides a comprehensive discussion of the different types of decision "problematiques"', i.e., choice, ranking, sorting. Thus it does not rank the alternatives, as typically happens in multicriteria techniques characterized by "γ" problematique, where the competing alternatives are ranked from best to worst. The shortcoming of techniques with the "γ" problematique, lies in the very high level of analyst/decision maker subjectivity. In fact, besides introducing (as in "α "problematique) a set of weights for each criterion, in this case the analyst/decision maker introduces another six subjective parameters, in order to determine the strict preference, indifference and veto thresholds.

Consequently, the level of randomness increases significantly, generating a less agreed upon choices that are thus less practical in transparent decision making processes, an essential and necessary condition in public administration.

For this reason, we decided to develop a new methodology, i.e. adapt one of the main “α “problematique techniques (concordance analysis) to a ranking procedure. This is done by applying the technique iteratively to a set of alternatives, from which, at each iteration, the best one is extracted. The sequence of alternatives thus extracted produces the required ranking.

In brief, concordance analysis is used in decision-making processes to support the choice among different alternatives in complex problems (Fadda, 2002). The safety factors represent the objective functions $g_1, g_2, g_3, \ldots, g_k$, that must be maximized or minimized, in order to obtain higher safety performance. The objective functions, involving the same issues, are grouped into homogeneous target areas: traffic accidents c_s, road geometry c_g, traffic flow c_f (Elvik R., 2005). Several sensitivity tests were conducted to determine the dependence of the solution on the weights assigned to the objective functions:

$$w_k, \sum_k w_k = 1 \tag{3}$$

The model proposed here finds the primary solution and also ranks the alternatives in accordance with safety intervention needs.

Concordance analysis is based on the pairwise comparison of alternatives. A dimensionless matrix is constructed, using the indicator values. The preferability of one alternative over the others is measured by means of the concordance and discordance indexes (Hinloopen and Nijkamp, 1990).

The model comprises 8 steps:

1.Identification of the alternatives a_h, h sections along a motorway are considered for the comparison;

2.Specification of objective functions g_k, k objective functions are considered to quantify the safety conditions.

3.Specification of decision matrix M_{ij}, $1 \leq i \leq k$, $1 \leq j \leq h$. The decision matrix is a two dimensional array k x h, where k rows are the objective functions g_k, the h columns are the alternatives a_h and the element p_{ij} is the value of the objective functions g_k for the alternative a_h.

4.Assigning weights w_k to the objective functions g_k. In this phase a hierarchy has been defined between the objective functions themselves. The weighting schemes are based on the recommendations put forward by the decision maker.

5.Concordance and discordance matrices. With the concordance – discordance method, two matrices need to be created by comparing the alternatives to define the system of final preferences.

The elements c_{ij} of the concordance matrix are defined as:

$$c_{ij} = \sum_{k \in Cij} (\mathrm{w}_k) \tag{4}$$

where:

$$C_{ij} = k : p_{ki} \geq p_{kj} \tag{5}$$

The elements d_{ij} of the discordance matrix are defined as:

$$d_{ij} = \frac{\sum_{k \in Dij} \left(\frac{\mathrm{w}_k \cdot \left| \left(p_{kj} - p_{ki} \right) \right|}{d_{\max}} \right)}{m} \tag{6}$$

where:

$$D_{ij} = k : p_{ki} \leq p_{kj}\ ,\ \forall i \neq j \qquad (7)$$

$$d_{\max} = \max\left\{w_i \left| p_{kj} - p_{ki} \right|\right\} \qquad (8)$$

$$m = \max_{ij}\text{, number of elements in } D_{ij} \qquad (9)$$

6. Concordance index Ic_i and Discordance index Id_i. The concordance index Ic_i symbolizes the total satisfaction of the decision-maker choosing the a_i alternative instead of the a_j:

$$Ic_i = \sum_j c_{ij} - \sum_j c_{ji} \qquad (10)$$

The discordance index Id_i reflects the regret of the decision-maker in choosing the a_i alternative instead of the a_j:

$$Id_i = \sum_j d_{ij} - \sum_j d_{ji} \qquad (11)$$

7. Comparing the alternatives. The alternatives are structured by increasing the concordance index and decreasing the discordance index to obtain two lists. The alternatives choice have a positive Ic_i and negative Id_i. The chosen alternative has a positive Ic_i and negative Id_i. (Giuliano, 1985). In cases where an alternative has a negative concordance index and/or positive discordance index, this not represents the best compromise solution and it is not considered for the choice.

8. Sensitivity Analysis. Once this preliminary analysis has been completed, the calculation is repeated, from step 4 to step 7, analysing the different sets of weights.

Once the best compromise solution has been identified, it is excluded from the set A (to be ranked first) and iteration resumes. The recursive procedure could be as follows::

Let concord(A_i) be the algorithm for concordance analysis on a set A_i of n alternatives. The first iteration of the algorithm (k= 1), is performed on the original set A_1 and calculates the best compromise alternative “a”:

$$a = concord(A_1) \qquad (12)$$

The next iterations k (k=2, …, n), will be executed on subsets A_k of the set A_1, such that at each iteration the best compromise solutions found in the previous iterations are excluded.

$$A_k = \left\{ A_1 - \sum_{i=1}^{k-1} concord(\mathrm{A_i}) \right\}, 2 \leq k \leq n \qquad (13)$$

3. Application

This technique was applied to a motorway located in Sardinia. A 100 km long stretch of this motorway was divided into 11 homogeneous sections of varying length but with similar characteristics as to traffic flow and topography. The motorway concerned runs the length of the island and is heavily trafficked, in some sections as many as 1500 vehicles/h travelling in both directions. However, flow distribution is not uniform but varies significantly, in some sections less than 300 vehicles/h). As the motorway is the main route across the island, a lot of inter-town traffic also travels along the same road.

Lastly, a significant number of accidents with casualties or damage to vehicles has been recorded, both in absolute terms and as a function of traffic flow.

In order to conduct the multicriteria analysis, we identified three different target areas for assessing each road section. These criteria were chosen as representative of the safety conditions of the road segments. This criteria were chosen as representative of the safety conditions of the road segments. Their choice is based on the assumption that the indicators should be easy to measure and they should be clear to the decision maker. They have been proposed also in Fancello *et al.* (2014).

- Mobility, i.e. that analyses those aspects associated with vehicle flow, traffic load distribution and the type of traffic recorded. This area comprises the following four objective functions (or criteria):
  - g_1, Peak-hour factor (PHF), the hourly volume during the maximum-volume hour of the day; divided by the peak 15-min flow rate within the peak hour; a measure of traffic demand fluctuation within the peak hour (HCM, 2000);
  - g_2, %hv, % heavy vehicles for lane group vol. ume;
  - g_3, ADT, Average Daily Traffic, measured in vehicles per day
  - g_4, degree of saturation, volume to capacity (v/c) ratio (HCM, 2000);
- Geometry, which takes into account the geometrical characteristics of the road section. In this case we only considered one objective function:
  - g5, adjustment factor for lane width (fW), The lane width adjustment factor, fw, accounts for the negative impact of narrow lanes on saturation flow rate and allows for an increased flow rate on wide lanes. Standard lane widths are 3.6 m (HCM, 2000);
- Safety, that takes into account the number of accidents, in both absolute and relative terms, as well as the social consequences that these events have on society as a whole. In this case we have five objective functions:
  - g_6, safety potential (SAPO), it is defined as the amount of accident costs per kilometre road length (cost density) that could be reduced if a road section would have a best practise design (European Commission, 2003);
  - g_7, number of fatalities every year as the result of an accident in the section considered;
  - g_8, number of persons injured every year as the result of an accident in the section considered;
  - g_9, number of accidents with damage only to property;
  - g_{10}, accident rate (Tif), the number of accident divided by vehicle flow multiply by number of km (Elvik *et al.* 2009).

The values of criteria g_1, g_2 and g_3, were obtained from the traffic data measured by traffic detectors or traffic data estimated using a macro simulation software. The values of criterion g_4 was obtained by taking direct measurements on site. The values of criteria g_5 and g_6, were computed from historical accident data in the period 2007-2011. The following Table 1, the decision matrix, shows the values of criteria for each alternative and each criterion

The Decision matrix is shown below:

Table 1. Decision matrix

criteri	1	2	3	4	5	6	7	8	9	10	12
Peak hour factor	0.89	0.91	0.91	0.91	0.91	0.91	0.91	0.92	0.92	0.93	0.94
% heavy vehicles	0.20	0.13	0.10	0.09	0.17	0.18	0.16	0.14	0.12	0.12	0.14
ADT	12,871	8,752	9,157	10,356	7,088	7,081	7,987	10,719	14,142	15,719	20,337
v/c	19.50	13.50	13.00	14.50	13.50	14.00	15.50	16.50	19.00	19.50	27.50
fW	0.81	0.83	0.82	0.81	0.80	0.81	0.82	0.82	0.83	0.80	0.79
SAPO	194.21	84.44	59.11	545.67	503.45	126.66	1,164,15	1,006.90	393.68	1,277.10	2,062.37
n° of fatalities	0	0	0	1	1	0	3	2	1	2	2
n° of injured	23	10	7	29	24	15	31	48	11	80	173
n° of accidents	13	6	5	20	17	10	17	34	8	52	94
Accident rate	0.09	0.08	0.04	0.15	0.19	0.10	0.11	0.08	0.08	0.36	0.36

Regarding the weights to be assigned to the objective functions, these were chosen as typically happens in concordance analysis, by indicating the weight for the target area alone and then dividing this into equal parts for each criterion. In this analysis four set of weights we have used. In the first one, the Decision Maker has assigned the same priority to all target areas. Mobility, Geometry and safety. Each target area receives a weight equal to 1/3 of the total weight. So that, the Decision Maker does not express any preferences among the target area. In the others set, a sensitivity analysis is conducted in order to determine changes in the ranking. Each target takes highest weight alternatively, in order to study significant changes, the weight is increased to twice of the others. These four sets are:

- Same weight assigned to all three areas;
- Twice the weight assigned to one area, the same weight to the other two

Table 2. Set of weights.

Objective functions		Goal Area	1	2	3	4
1	Peak hour factor	1	0.0833	0.1250	0.0625	0.0625
2	% high vehicle	1	0.0833	0.1250	0.0625	0.0625
3	ADT	1	0.0833	0.1250	0.0625	0.0625
4	v/c	1	0.0833	0.1250	0.0625	0.0625
5	Width adjustment factor (fW)	2	0.3333	0.2500	0.0500	0.2500
6	SAPO	3	0.0667	0.0500	0.0500	0.1000
7	n° of fatalities	3	0.0667	0.0500	0.0500	0.1000
8	Number of injured	3	0.0667	0.0500	0.0500	0.1000
9	Number of accidents	3	0.0667	0.0500	0.0500	0.1000
10	Accident rate	3	0.0667	0.0500	0.0500	0.1000

By so doing it was also possible to conduct a sensitivity analysis on the solution, evaluating its stability versus the weight of each criterion.

4. Results

The results are given in the table below that shows the overall concordance (Ic) and discordance (Id) indexes for each of the four sets of weights.

- The first iteration shows that the choice falls on Section 12, i.e. the section that, on the basis of the defined criteria, is the most in need of safety interventions. Note the very high values of Ic for all four sets of weights, while the values of Id are significantly lower. This iteration only singled out sections 12, 1 and 8. The complete table is shown below.

Table 3. 1st iteration

TARGET AREA SCENARIOS

				1		2		3		4		5		6		7		8		9		10		12	
	Mobility	Geometry	Safety	Ic_1	Id_1	Ic_2	Id_2	Ic_3	Id_3	Ic_4	Id_4	Ic_5	Id_5	Ic_6	Id_6	Ic_7	Id_7	Ic_8	Id_8	Ic_9	Id_9	Ic_{10}	Id_{10}	Ic_{11}	Id_{11}
weights	33.33%	33.33%	33.33%	0.450	-0.663													0.700	-0.634					8.767	-1.378
	50%	25%	25%	1.025	-0.232													1.150	-0.671					8.450	-0.564
	25%	50%	25%	0.838	-0.784																			9.075	-1.565
	25%	25%	50%															1.425	-0.540					8.775	-0.535

- The second iteration, performed on 10 road sections, selected section No.8 as first choice. As opposed to the first iteration, in this case the outcome for the four sets of weights was not so clear-cut; for example for the 3rd set of weights the choice fell on section No.1. For this reason, in this specific case we decided to introduce another set of weights so as to better evaluate solution sensitivity, assigning in turn three times the weight to one target area and the same weight to the other two. Here too, the prevalence of section No. 8 was not unequivocal (in one case it was not even identified as an acceptable solution). Significantly increasing the weight of each area over the others (0.80 over 0.10) produced the same results. Note that in this case sections Nos. 4 and 6 were also identified as acceptable solutions, (not so in the previous iteration), as the solution is selected by pairwise comparison of the alternatives and not in absolute terms. The complete table is shown below.

Table 4. 2nd iteration, set of weights 1

TARGET AREA **SCENARIOS**

				1		2		3		4		5		6		7		8		9		10	
	Mobility	Geometry	Safety	Ic_1	Id_1	Ic_2	Id_2	Ic_3	Id_3	Ic_4	Id_4	Ic_5	Id_5	Ic_6	Id_6	Ic_7	Id_7	Ic_8	Id_8	Ic_9	Id_9	Ic_{10}	Id_{10}
weights	33.33%	33.33%	33.33%	1.283	-0.027					0.967	-0.062							1.467	-1.226				
	50%	25%	25%															1.850	-1.193				
	25%	50%	25%	1.713	-0.153					1.475	-0.379			0.450	-0.262			0.350	-0.800				
	25%	25%	50%	0.363	-0.436					1.575	-0.120							2.200	-1.064				

Table 5. 2nd iteration, set of weights 2

TARGET AREA **SCENARIOS**

				1		2		3		4		5		6		7		8		9		10	
	Mobility	Geometry	Safety	Ic_1	Id_1	Ic_2	Id_2	Ic_3	Id_3	Ic_4	Id_4	Ic_5	Id_5	Ic_6	Id_6	Ic_7	Id_7	Ic_8	Id_8	Ic_9	Id_9	Ic_{10}	Id_{10}
weights	60%	20%	20%															2.080	-1.277	0.200	-0.030		
	20%	60%	20%	1.970	-0.278					1.780	-0.461			0.960	-0.247								
	20%	20%	60%							1.940	-0.079							2.640	-0.958				

Table 6. 2nd iteration, set of weights 3

TARGET AREA **SCENARIOS**

				1		2		3		4		5		6		7		8		9		10	
	Mobility	Geometry	Safety	Ic_1	Id_1	Ic_2	Id_2	Ic_3	Id_3	Ic_4	Id_4	Ic_5	Id_5	Ic_6	Id_6	Ic_7	Id_7	Ic_8	Id_8	Ic_9	Id_9	Ic_{10}	Id_{10}
weights	80%	10%	10%															2.540	-0.589	2.100	-0.350		
	10%	80%	10%	2.485	-0.030																		
	10%	10%	80%															3.520	-0.859				

- The third iteration performed on 9 road sections identified No. 1 as the section most in need of maintenance. Similarly to the previous iteration, no clear-cut solution emerged for the four sets of weights. Here again it was necessary to introduce the same two additional sets of weights used in the previous iteration. The overall results were in this case even less well-defined than in the second iteration, insofar as with the first set of weights (0.50-0.25-0.25) section No.1 for once was not identified as one of the acceptable solutions; the same goes for the second (0.60-0.20-0.20) and third (0.80-0.10-0.10) set of weights, where No.1 is only singled out once as an acceptable solution. This iteration also identified sections Nos. 4, 6 and 9 as acceptable solutions, though not so frequently as in the second iteration. The complete table is shown below:

Table 7. 3rd iteration, set of weights 1

TARGET AREA SCENARIOS

				1		2		3		4		5		6		7		9		10	
	Mobility	Geometry	Safety	Ic_1	Id_1	Ic_2	Id_2	Ic_3	Id_3	Ic_4	Id_4	Ic_5	Id_5	Ic_6	Id_6	Ic_7	Id_7	Ic_9	Id_9	Ic_{10}	Id_{10}
weights	33.33%	33.33%	33.33%	0.983	-0.184																
	50%	25%	25%																		
	25%	50%	25%	1.238	-0.275					1.375	-0.146			0.225	-0.223						
	25%	25%	50%	0.288	-0.572					1.875	-0.042										

Table 8. 3rd iteration, set of weights 2

TARGET AREA SCENARIOS

				1		2		3		4		5		6		7		9		10	
	Mobility	Geometry	Safety	Ic_1	Id_1	Ic_2	Id_2	Ic_3	Id_3	Ic_4	Id_4	Ic_5	Id_5	Ic_6	Id_6	Ic_7	Id_7	Ic_9	Id_9	Ic_{10}	Id_{10}
weights	60.00%	20.00%	20.00%															0.300	-0.140		
	20.00%	60.00%	20.00%	1.390	-0.365					1.500	-0.067			0.580	-0.108						
	20.00%	20.00%	60.00%																		

Table 9. 3rd iteration, set of weights 3

TARGET AREA SCENARIOS

				1		2		3		4		5		6		7		9		10	
	Mobility	Geometry	Safety	Ic_1	Id_1	Ic_2	Id_2	Ic_3	Id_3	Ic_4	Id_4	Ic_5	Id_5	Ic_6	Id_6	Ic_7	Id_7	Ic_9	Id_9	Ic_{10}	Id_{10}
weights	80%	10%	10%															1.900	-0.204		
	10%	80%	10%	1.695	-0.146																
	10%	10%	80%																		

5. Conclusions

In this paper we have described a multicriteria method that provides support to administrator of the road when he analyzes safety conditions of the road network. This multicriteria method, called “Concordance Analysis” is derived from Electre I and solves problems of choice of the best compromise solution among various alternatives (“α“ problematique). In this paper this method is used for the first time in order to solves the problem of ranking (“γ” problematique) in inderect way. This is due to the fact the multicriteria method which solves “γ” problematique, such as Electre III, require a large number of parameters: weights and different thresholds assigned by authorities of the road. This methodology is applied to a case study. Different road segments of a motorway is analysed in order to identify the road segments with the worst safety conditions. According to the analysis, the segments with the worst safety conditions are the n. 12. This element is extracted from the set of alternatives and the analysis proceeds on the remaining elements. So that a partial ranking of road elements with worst safety conditions is obtained: Segments n.12 (1st), n.8 (2nd), n.1 (3rd). To check the robustness of the results we have conducted a sensitivity analysis by varying the weights of the criteria. The sensitivity analysis confirm the results. Thus, this easy-to-use, simplified technique with reduced randomness aspects could well be adopted for addressing ranking issues, generally dealt with and analysed using more complex techniques in terms of implementation and computational effort.

This proposed methodology has the following limitations:

- The choice of objective functions is based on the assumption that they should be easy to measure and they should be clear to the decision maker. However may be less representative than others;
- A complete ranking of all admissibile options is not defined through this methodology. When no alternative has a positive Ic and negative Id, the model does not provide information about the choice of elements with worste safety conditions.

Future research will focus on:

- Introducing new criteria that are able to deepen the analysis detail level, such as Road Maintenance Condition Indicators, for example;
- Trade-off analysis between concordance and discordance indices;
- Comparison of the results using a specific technique for “γ” problematique such as Electre III for example.

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