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A decision support system based on Electre III for safety analysis in a suburban road network

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Abstract

The aim of this paper is to develop a method for supporting decision makers in transport planning. When funds are insufficient to cover the interventions required to ensure safe driving conditions, it is necessary to optimize resources for the most critical sections. In this analysis, the multicriteria ranking method based on the ELECTRE III algorithms is applied to a real case, involving different sections of a motorway. This analysis is based on a comparison of different road sections in regard to safety conditions. The rank of more critical sections identifies intervention priorities.

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Keywords: multicriteria analysis ; Electre III ; road safety ; performance indicators

1. Introduction

Among the many research topics associated with traffic flows on road networks, road safety is becoming increasingly important. In 2010 there were 211,404 road accidents in Italy with damage to persons and things, resulting in a social cost of 28.5 billion Euros (Department for Transport of Italy, 2012). The year 2011 was marked by the launch of the United Nations Decade of Action for Road Safety. For this occasion, the United Nations called on member states, international agencies, civil society, businesses and community leaders to ensure real improvements and recommended governments to develop national action plans for the decade 2011-2020. As a response, in 2011 several countries issued or updated their national road safety strategies (OECD, 2013).

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Furthermore, one of the objectives indicated in the European Commission's document "Towards a European road safety area: policy orientations on road safety 2011-2020", concerns safer road infrastructure, to be achieved through promoting "the application of the relevant principles on infrastructure safety management to secondary roads of member states, in particular through the exchange of best practices" (European Commission, 2010). To attenuate the impact of this problem in terms of social and human costs, road safety needs to be viewed as forming an essential part of all stages of transport network planning.

Analyses of the safety conditions of road sections points to those demand and supply characteristics that significantly affect the occurrence of harmful events and the extent of the consequences on road users. The findings also make it possible to define those actions necessary to overcome or mitigate the negative effects. Poor road safety increases both the risk of accidents and the health costs associated with the consequences of the physical injuries sustained by pedestrians, drivers and passengers involved in these events. The analysis of the safety conditions highlights characteristics that affect the occurrence of harmful events. Leaving aside human and vehicle factors, that are beyond the scope of the present work, here we determine the safety conditions of a road sections as depending on environment factors, for exemple traffic flow and road characteristics. (Karlaftis & Golias, 2002). The traffic flow characteristics reported in the literature as having a significant effect on the level of safety include the presence of heavy vehicles, traffic intensity and vehicle density (Martin, 2002). The geometrical characteristics on the other hand include lane width, the presence of shoulders, curvature, surface regularity (Zegeer, 1980).

Road infrastructure safety interventions need to be planned on the basis of available resources of the competent authority. In the event funds are insufficient to cover all the interventions required to restore and maintain safe driving conditions in the road network, then it will be necessary to hierarchise the infrastructure according to safety conditions. By so doing, priority will be given to interventions on roads with worst safety conditions and where there exists a greater risk of accidents. Thus it is important for the authority of the road to intervene on those sections of the network that have been assigned greatest priority by the hierarchical analysis conducted according to specific safety criteria (Dell'Acqua et al., 2011). This requires a decision support tool that is able to analyse the conditions of the different roads and guide the choice of interventions. A number of published studies address the conditions of road infrastructures both in general terms and related specifically to safety. Fierek and Zak describe a planning system for an integrated urban transport system based on a macro-simulation, evaluating different scenarios by means of multicriteria analysis using the Electre III / IV method (Fierek & Zak, 2012), Fancello proposes a methodology for evaluating network functionality analyzing several aspects that commonly affect operating conditions such as traffic flow, safety, accessibility and environmental impact (Fancello et al., 2013). In the specific area of road safety, Dell'Acqua present a model for classifying black spots in road networks using a decision support system (DSS) based on cluster analysis techniques. With this system it is possible to identify and rank hazardous road locations and establish terms for an infrastructure scheme aimed at reducing the risk of accidents (Dell'Acqua et al., 2011). Greibe develops a simple, practicable accident model that predicts, as accurately as possible, the expected number of accidents at urban junctions and road links. The model can be used to identify factors affecting road safety, in particular 'black spots' identification and to support network safety analysis undertaken by local road authorities (Greibe, 2003). Thus the present paper aims to develop a decision support model for comparing and ranking different roads according to specific safety criteria. The model will provide a support to decision makers for allocating available resources to road infrastructures.

2. Methodology

Among several multicriteria analysis proposed in the scientific literature, the Electre III method defines a ranking of alternatives, on the basis of evaluation criteria. Many authors use this ranking method in various fields: Cavallaro and Papadopoulos in renewable energy sources field (Cavallaro, 2010; Papadopulos, 2008), Giannoulis in order to ranking British Universities (Giannoulis, 2010), Karagiannidis and Moussiopoulos in the area of municipal solid waste management (Karagiannidis & Moussiopoulos, 1997). In particular, in the transport planning field, Fierek and Zak use the method Electre III in order to solve complex transportation decision problems (Zak & Fierek, 2007; Zak 2011). Method Electre III compares alternatives using the binary outranking relation that generates a hierarchical ranking (Roy, 1975 ; Roy, 1976 ; Tille and Dumont, 2003). The Electre III is a method for classifying n actions, on the basis of evaluation criteria g_j, $j \in F$, where $F = \{g_1, g_2, g_3,\dots,g_m\}$.

In the Electre III method the outranking relation is constructed on the basis of the degree of credibility which, comparing a and b, a pair of elements of the set to be ranked, is attributed to the proposition “a is at least as good as b”. When the two elements a e b are evaluated on the basis of the criterion j, if the criterion j is a real criterion then we get:

$$aP_jb \Leftrightarrow g_j(\mathrm{a}) > g_j(b) \text{ a is strictly preferred to b over criterion j} \tag{1}$$

$$aI_jb \Leftrightarrow g_j(\mathrm{a}) = g_j(b) \text{ a is indifferent to b over criterion j} \tag{2}$$

One can also distinguish between true criteria and pseudo-criteria so as to also account for those elements with a certain margin of imprecision. For $g_j(b) \geq g_j(a)$:

$$bIa \Leftrightarrow g_j(b) - g_j(a) \leq \mathrm{q_j[g_j(a)]} \tag{3}$$

$$bQa \Leftrightarrow q_j[\mathrm{g_j(a)}] < \mathrm{g_j(b)} - \mathrm{g}_j\mathrm{(a)} \leq \mathrm{p_j[g_j(a)]} \tag{4}$$

$$bPa \Leftrightarrow g_j(b) - g_j(a) > p_\mathrm{j}[\mathrm{g_j(a)}] \tag{5}$$

Where $q_{ij}[g_j(a)]$ is the indifference threshold associated with the pseudo-criterion j and $p_j[g_j(a)]$ is the strict preference threshold associated with the pseudo-criterion j;

The Electre III model considers the indifference and strict preference thresholds so as to account for the difference in performance between the two alternatives with respect to the criterion. These two thresholds are the functions:

$$p_\mathrm{j} = f(\mathrm{g_j}(a)) = \alpha_p \times g_j(a) + \beta_p \tag{6}$$

$$q_\mathrm{j} = f(\mathrm{g_j}(a)) = \alpha_q \times g_j(a) + \beta_q \tag{7}$$

where the coefficients α_p, α_q, β_p, β_q have to be assigned for each criterion. Further, to each criterion a weight w_j is assigned with

$$\sum_{j=1}^{m} w_j = 1,\ w_j > 0,\ \forall j \in F \tag{8}$$

that represents the relative importance that the decision maker assigns to the pseudocriteria of F.

Another threshold also needs to be considered, the veto threshold v_j of the criterion j, defined as the difference

$$u = g_j(b) - g_j(a) \tag{9}$$

based on which it can be said that “b is so much better than a for $g_j(a)$ that in any case a shall be considered better than b, whatever the performance of a over b over all the other criteria:

$$bPV_j \Leftrightarrow v_j[\mathrm{g_j(a)}] < g_\mathrm{j}(\mathrm{b}) - g_\mathrm{j}(\mathrm{a}) \tag{10}$$

The outranking relation in the Electre III method is constructed using concordance and discordance techniques (Roy, 1973). The concordance index measures the strength of support, given the available evidence, that a is at least as good as b. Concordance index $c_j(a,b)$ over alternatives a and b with respect to the criterion j:

$$c_j(a,b) = \begin{cases} 0, \text{if } g_j(b) \geq g_j(a) + p_j(g_j(a)) \\ 1, \text{if } g_j(b) \leq g_j(a) + q_j(g_j(a)) \\ \dfrac{g_j(a) + p_j(g_j(a)) - g_j(b)}{p_j(g_j(a)) - q_j(g_j(a))}, \textit{otherwise} \end{cases} \tag{11}$$

Overall concordance index over alternatives a and b considering all criteria C(a,b):

$$C(a,b) = \frac{\sum_{j=1}^{m} w_j \cdot c_j(a,b)}{\sum_{j=1}^{m} w_j} \tag{12}$$

Discordance index D(a,b) measures the strength of the evidence against this hypothesis. $D_j(a,b)$ discordance index over alternatives a and b with respect to the criterion j:

$$D_j(a,b) = \begin{cases} 0, \text{if } g_j(b) \leq g_j(a) + p_j(g_j(a)) \\ 1, \text{if } g_j(b) \geq g_j(a) + v_j(g_j(a)) \\ \dfrac{g_j(b) - g_j(a) - p_j(gj(a))}{v_j(g_j(a)) - p_j(g_j(a))}, \textit{otherwise} \end{cases} \tag{13}$$

If no veto threshold v_j is specified, then $D_j(a,b)$ is equal to 0 for all pairs of alternatives.

Credibility index S(a,b) measures the strength of the claim that “alternative a is at least as good as alternative b”.

$$S(a,b) = \begin{cases} C(a,b), \text{if } D_j(a,b) \leq C(a,b)\ \forall j \\ C(a,b) \cdot \prod_{D_j(a,b) > C(a,b)} \dfrac{1 - D_j(a,b)}{1 - C(a,b)}, \textit{otherwise} \end{cases} \tag{14}$$

The ranking algorithm is based on the degree of credibility of each element. One obtains two partial pre-orders that combined provide the overall ranking, according to an algorithm that is described in detail in (Roy, 1978).

3. Application

The methodology described above was applied to a real case study. We analysed a suburban road system in Sardinia, Italy. The system consists of a motorway that runs the length of the island. This major route has been divided into 10 homogeneous sections a_i, $1 \leq i \leq 10$. To assess the safety conditions of each section a_i we defined six safety criteria g_i, $1 \leq i \leq 6$. These criteria g_i were determined by means of direct surveys and analysis of historical road accident data. The safety criteria are are specified in the following:

- 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 (Manual H. C., 2000);
- g_2, %hv, % heavy vehicles for lane group volume;

- g_3, degree of saturation, volume to capacity (v/c) ratio (Manual H. C., 2000);
- g_4, 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 (Manual H. C., 2000);
- g_5, safety potential (SAPO), defined as the accident costs per kilometre of road during the selected period 2007÷2011 (cost density) that could be reduced had a road section been designed according to best practices (European Commission, 2003).
- g_6, accident rate (Tif), the number of accidents divided by vehicle flow multiplied by the number of km during the selected period 2007÷2011 (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.

Table 1. The Decision matrix

	g_1	g_2	g_3	g_4	g_5	g_6
a_1	0.887	0.199	0.483	0.81	9.85	0.13
a_2	0.887	0.198	0.527	0.81	0	0.092
a_3	0.907	0.132	0.252	0.83	20.6	0.075
a_4	0.907	0.105	0.25	0.82	8.61	0.043
a_5	0.907	0.093	0.327	0.81	67.61	0.151
a_6	0.912	0.172	0.543	0.80	90.21	0.188
a_7	0.912	0.176	0.322	0.81	34.18	0.097
a_8	0.912	0.156	0.436	0.82	116.25	0.106
a_9	0.920	0.144	0.396	0.82	34.43	0.083
a_{10}	0.923	0.123	0.336	0.83	54.91	0.077

It is up to the decision-maker to specify, for each criterion, the value of the weight w_j, the preference direction, the values of the coefficients of indifference α_p and β_p, the coefficients of preference α_q and β_q and the veto threshold v_j. The weight represents the relative importance of each criterion. In this application the weights are not normalised and they can take a positive value lower than one hundred. Each criterion g_j has an increasing preference direction if the greatest values are the most critical ones, i.e. if the objective is to maximise the criterion j.

Viceversa, the preference direction decreases if the lowest values are the most critical ones and the objective is to minimise the criterion j. In the present analysis the preference and indifference thresholds are equal and there is no veto involved. This choice is justified in order to allow comparison with our previous study “A decision support system for road safety analysis” (Fancello et al., 2013) based on method Electre I that does not consider the indifference, preference and veto thresholds. In that study we have applied a method derived from Electre I based on the concordance technique (Giuliano, 1985), that solves the problems of choice, problem α, in order to solves a ranking procedure, problem γ, in an indirect way. This is done by applying the method Electre I 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.

The weights and preference thresholds were assigned on the basis of the preferences of a hypothetical decision maker who uses the decision support model to identify those parts of the road infrastructure with the most critical safety conditions, in keeping with the objective of the present work.

The values of the parameters are given in Table 2

Table 2. Definition of the pseudo-criteria

criterion	weight	preferences	coefficients of indifference		coefficients of preferences	
g_j	w_j		α_p	α_q	β_p	β_q
g_1	0.1	decreasing	0.025	0	0.025	0
g_2	0.1	increasing	0.050	0	0.050	0
g_3	0.1	increasing	0.025	0	0.025	0
g_4	0.2	decreasing	0.100	0	0.100	0
g_5	0.25	increasing	0.020	0	0.020	0
g_6	0.25	increasing	0.020	0	0.020	0

The table 3 shows the Concordance matrix C(a,b):

Table 3. The Concordance matrix

	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_{10}
a_1	1	0.9	0.75	1	0.5	0.4	0.75	0.75	0.75	0.75
a_2	0.5	1	0.75	0.75	0.5	0.4	0.5	0.5	0.75	0.75
a_3	0.55	0.55	1	1	0.4	0.3	0.3	0.3	0.3	0.4
a_4	0.3	0.55	0.4	1	0.4	0.3	0.3	0.3	0.3	0.3
a_5	0.8	0.8	0.9	0.9	1	0.3	0.9	0.55	0.8	0.8
a_6	0.8	0.8	1	1	1	1	1	0.75	1	1
a_7	0.45	0.7	1	1	0.5	0.4	1	0.4	0.9	0.65
a_8	0.45	0.7	1	1	0.75	0.55	0.9	1	1	1
a_9	0.45	0.45	1	1	0.5	0.3	0.65	0.3	1	0.75
a_{10}	0.45	0.45	0.9	1	0.5	0.3	0.65	0.3	0.55	1

Discordance index Dj(a,b) is equal to 0 for all pairs of alternatives if the veto threshold is not considered and in this case the Credibility matrix S(a,b) is equal to the Concordance Matrix C(a,b).

Application of the multicriteria analysis model produced the final ranking, where the alternatives are ranked in descending order, from the most critical safety conditions (1st) for alternative a_6, to the least critical (7th) alternative a_4. The alternatives a_1 and a_8 have the same criticality degree and have both been ranked in 2nd place. The same goes for the alternatives a_2, a_7 and a_{10} all ranked in 4th place. Table 4 shows the Ranking matrix, where P if alternative a_i is better than alternative a_j, I if alternative a_i is equivalent to alternative a_j, P^{-} if alternative a_i is as good as to alternative a_j, R if alternative a_i is incomparable to alternative a_j.

Table 4. The Ranking matrix

	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_{10}
a_1	I	P	P	P	R	P^{-}	R	R	P	P
a_2	P^{-}	I	R	P	P^{-}	P^{-}	R	P^{-}	R	R
a_3	P^{-}	R	I	P	P^{-}	P^{-}	P^{-}	P^{-}	P^{-}	P^{-}
a_4	P^{-}	P^{-}	P^{-}	I	P^{-}	P^{-}	P^{-}	P^{-}	P^{-}	P^{-}
a_5	R	P	P	P	I	P^{-}	P	P^{-}	P	P
a_6	P	P	P	P	P	I	P	P	P	P
a_7	R	R	P	P	P^{-}	P^{-}	I	P^{-}	P	R
a_8	R	P	P	P	P	P^{-}	P	I	P	P
a_9	P^{-}	R	P	P	P^{-}	P^{-}	P^{-}	P^{-}	I	R
a_{10}	P^{-}	R	P	P	P^{-}	P^{-}	R	P^{-}	R	I

Table 5 shows the final ranking:

Table 5. Ranking of alternatives

ranking	
1st	a_6
2nd	a_1, a_8
3rd	a_5
4th	a_2, a_7, a_{10}
5th	a_9
6th	a_3
7th	a_4

To check the robustness of the results we conducted a sensitivity analysis. The alternatives ranking was checked by varying the weight w_j of the criteria. Here we restricted the sensitivity analysis to the variability of the criteria weights w_j omitting any further analysis of the dependence of ranking on the variability of the coefficients of indifference α_p, β_p and coefficients of preference α_q, β_q. To evaluate the effect of varying the weight of each criterion on the ranking of the alternatives, the weights were varied alternately. To restrict the number of possible combinations due to the presence of the six criteria g_j, the criteria were grouped into three macrocriteria z_k, k = 1,…,3, according to their characteristics.

$$z_1 = \{g_1, g_2, g_3\} \text{, flow} \tag{15}$$

$$z_2 = \{g_4\} \text{, geometry} \tag{16}$$

$$z_1 = \{g_1, g_2, g_3\} \text{, historical accident data} \tag{17}$$

The weights ϑ_k, k = 1,…,3 of the macrocriteria were determined as follows:

$$\vartheta_1 = w_1 + w_2 + w_3,\ w_1 = w_2 = w_3 \tag{18}$$

$$\vartheta_2 = w_4 \tag{19}$$

$$\vartheta_3 = w_5 + w_6 \tag{20}$$

Three sets of weights P_1, P_2, P_3 were defined. For each set, the six combinations S = {s_2, s_3, s_4, s_5, s_6, s_7} were tested, where each weight ϑ_k of the macrocriteria z_k were alternately changed for a total of 18 test. In the first set P_1, the weights were alternately reduced by 25% and increased by 25%, in the second set P_2 were reduced by 35% and increased by 35% and in the third set P_3 were reduced by 50% and increased by 50%. The sets are shown in Table 6, 7 and 8.

Table 6. Set of weights P_1, ±25%

	s_2	s_3	s_4	s_5	s_6	s_7
ϑ_1	0.225	0.375	0.300	0.300	0.300	0.300
ϑ_2	0.200	0.200	0.150	0.250	0.200	0.200
ϑ_3	0.500	0.500	0.500	0.500	0.375	0.625

Table 7. Set of weights P_2, ±35%

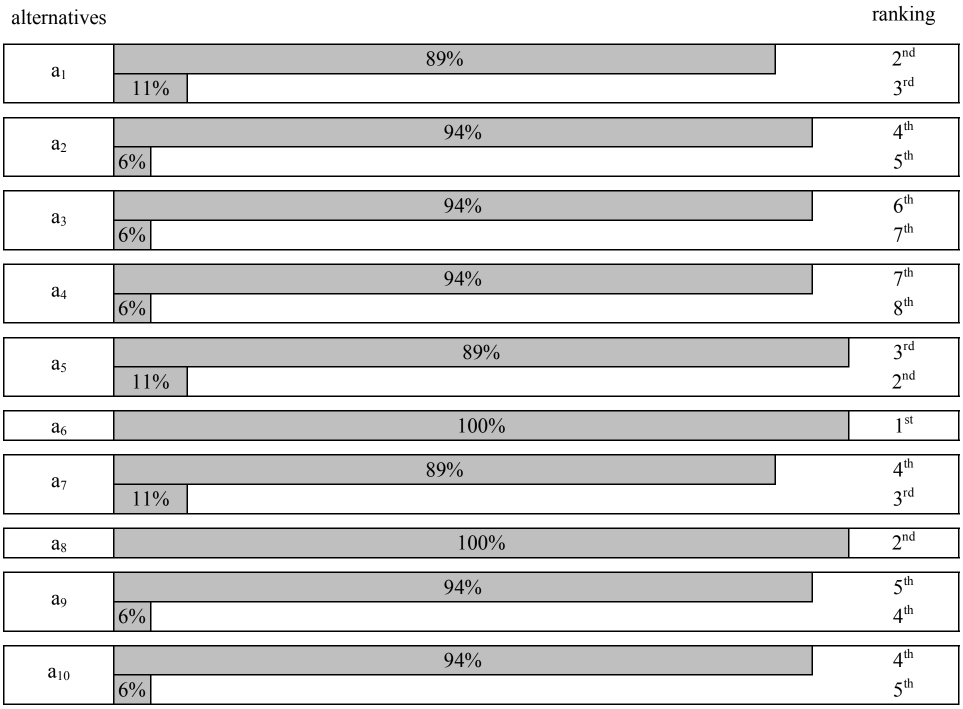
	s_2	s_3	s_4	s_5	s_6	s_7
ϑ_1	0.195	0.405	0.300	0.300	0.300	0.300
ϑ_2	0.200	0.200	0.130	0.270	0.200	0.200
ϑ_3	0.500	0.500	0.500	0.500	0.325	0.675

Table 8. Set of weights P_3, , ±50%

	s_2	s_3	s_4	s_5	s_6	s_7
ϑ_1	0.150	0.450	0.300	0.300	0.300	0.300
ϑ_2	0.200	0.200	0.100	0.300	0.200	0.200
ϑ_3	0.500	0.500	0.500	0.500	0.250	0.750

When the weight ϑ_1 of the macrocriterion z_1 is reduced by 35%, the alternatives a_5 and a_7 rank one place higher, while the alternative a_1 drops one place. The same happens when the weight ϑ_1 is reduced by 50%, but in this case the alternative a_2 also moves down one place. When the weight ϑ_3 of the macrocriterion z_3 is reduced by 50%, the alternative a_9 moves up one place in the ranking, the alternative a_{10} drops one place while the alternative a_7 moves down two places. Further variations in the criteria weights indicated in Tables 6, 7 and 8, did not affect the rankings calculated the first time and shown in Table 7. The graph shows the percentage of times that the alternatives obtain the rank indicated. The sensitivity analysis confirms the results and the ranking of the alternatives does not change significantly.

Table 9. Sensitivity analysis



4. Conclusion

The aim of the present work was to specify a decision support model for planning safety interventions in road infrastructures. The model assists public administrations in those cases where available financial resources are insufficient to cover all the interventions required, by ranking the sections according to the safety conditions. These are evaluated using criteria that provide a measure of performance under specific operating conditions. By applying the model it is possible to allocate available funds to infrastructures with the most critical safety conditions. Application of the model made it possible to rank the road sections as a function of safety conditions. Those ranked in the top places are in the most critical conditions. This classification makes it possible to identify those sections of the motorway where priority needs to be given to safety interventions. In the case at hand it was applied to a case study concerning a motorway in Sardinia, Italy. In accordance with the criteria chosen and the weights assigned, the 10 road sections considered were ranked according to safety conditions. In the specific case, in allocating available funds, priority should be given to safety interventions on road sections a6. Funds should be allocated according to rank, in the hierarchical order: a_6; a_1 and a_8; a_5; a_2, a_7 and a_{10}; a_9; a_3; a_4.

Further sensitivity analyses showed this ranking to be a stable solution as varying the weights of the criteria weight did not produce any significant changes. Minor variations in the alternatives ranking occur in particular when varying the weight ϑ_1 of the macrocriterion of traffic flow z_1, as this affects solution stability for negative variations from 35% upwards. For variations in weight of -50%, the ranking also becomes more sensitive to the weight ϑ_3 of the macrocriterion of safety z_3.

This research work is the first step towards defining a decision support methodology in road safety planning. Further developments of the model are currently under way to increase the meaningfulness of the safety indicators. Different values for the indifference and preference thresholds can be introduced in order to consider imprecise data. Further methods will be analyzed in order to reduce the arbitrariness of the thresholds.

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