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Using multicriteria decision analysis to assess the sustainable safety performance of road projects at the design stage

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Over the past decade, the improvement of road safety had been a major issue in transport policies in Europe. Simultaneously the concept of sustainable development has become a key element in many strategic and operational policies – including the road sector policies. However, considering the design stage of road infrastructure projects, there are almost no methodology that both quantify the road safety performance and consider the sustainable concerns. This study seeks to develop a preventive evaluation model based on multicriteria decision analysis and that will allow designers to assess the sustainable safety performance of their road projects. In this paper, we describe the theoretical concept of sustainable road safety and we address the multicriteria problem by detailing the set of considered criteria. We introduce the multicriteria approach on an illustrative example. Finally, the current and future developments on the multiobjective mathematical model are briefly presented.

Keywords: multicriteria analysis, road design, safety, sustainability.

1. Introduction

For many years, considering sustainable development and improving road safety have been two majors concerns in mobility and transport policies in Europe. Since 2001, the European Commission had published several reports and directives about the improvement of the safety level on the European road network.
In the European White Paper on Transport Policy (European Commission, 2001), an objective of halving the overall number of road deaths in the European Union by 2010 had been targeted. This challenging objective has been updated and reinforced in the Road Safety Programme 2011-2020. It has been completed with several strategic objectives and principles such as the development of an integrated approach to road safety (European Commission, 2010). In 2003, the European Road Safety Charter had been published and submitted to several actors of the road sector, as a commitment to take concrete actions in order to reduce road accident fatalities. Additionally, in 2010, the European Commission had published the Greening Transport Package about strategies to apply in order to strive for a transport system more respectful of the environment.
In Belgium, the Federal Commission for the Road Safety had been formed in 2002 with intent to fulfil the objectives of the European Commission. In 2011, the initiative “Go For

Zero" has been launched by the State Secretary for Mobility and the Belgian Institute for Road Safety. It conducts several actions to make the road users sensitive to road safety issues (e.g. speed, seatbelt, alcohol and driving, etc.). In Wallonia, the government reaffirmed its willingness to promote sustainable mobility for every road users in its declaration of regional policy for the period 2009-2014.

2. Research motivation

2.1 Towards a preventive evaluation of road safety

To date, the assessment of the road safety performances of an infrastructure is essentially based on reactive approaches such as the evaluation of databases containing accident statistics. These offer the administration a support in the identification of the areas or routes with high accident concentration – also called black spots. These methods consist of curative analysis and handling of the high accident concentration areas. However, to meet the objectives of improving road safety and considering sustainable character of the road transport infrastructure, it has become essential to develop new preventive and innovative tools.

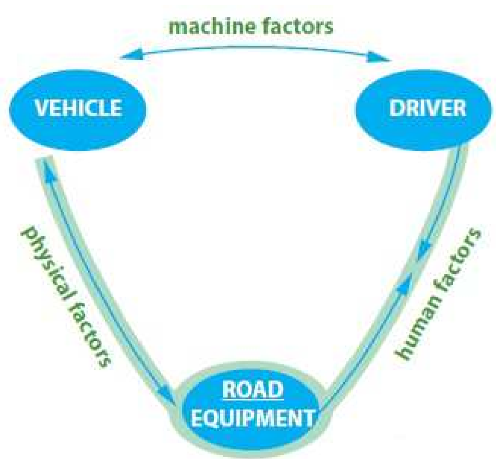

Figure 1. Elementary triangle of road safety

At first, it is important to define theoretically what road safety is. To do so, we can use the elementary triangle of road safety (cf. Figure 1 above) which is composed of the dimensions vehicle, driver and road equipment. On the basis of this triangle, we are able to classify all the causes of an accident in one or more of the three main dimensions (i.e. apexes of the triangle) or their interactions (i.e. sides of the triangle). If we want to improve the global level of road safety of an infrastructure, we have to take an interest in one or some of these triangle components. Within the framework of this research, we are focusing on the road equipment dimension and the human and physical factors. Indeed, according to different studies, from 18% to 28% of the accidents are due to an unsafe road environment or infrastructure (OECD, 1999). For methodological reasons, we are focusing in this study on the secondary rural roads of the Belgian network.

2.2 An integrated and sustainable approach of road safety

Considering the major environmental, economic and social crisis that the world has experienced, and due to the collective nature of a road infrastructure, it has become crucial to integrate the road sector policies into a more sustainable approach. Indeed, road safety has close links with some sustainable topics such as energy consumption, preservation of environment, economic performance, noise disturbance or even social impact. In practice, it both implies to reconsider current policies by taking into account sustainable development concerns and to develop some new evaluation processes and decision aiding tools to offer road sector a common definition about sustainability. As mentioned below, several reports have been published during the past years by national and European organizations in order to promote sustainable roads. In this research project, we have decided to enrich the evaluation of the safety performance of road projects with some fundamental concerns related to the environmental, social and economic dimensions of sustainable development. By doing so, we define a more complete and integrated assessment model which would meet the needs of the transport and mobility policies in Europe.

2.3 A support to innovative projects

During the design stage of a road infrastructure, several alternatives are modeled by the engineers in charge of the project. Different design choices are made by varying several parameters that represent the main characteristics of the project (e.g. number of lanes, lane width, nature of an eventual cycle lane, nature of the road signs or vehicle restraint systems, type of intersections, etc.). At the end of this modeling stage, an alternative is selected among all of those that were modeled (cf. Figure 2 below). But even if this selection is not exclusively motivated by the economic criterion, there is to date no integrated tool that could help the design engineers to analyze each alternative and to select the most appropriate to the challenges and the stakes of the project.

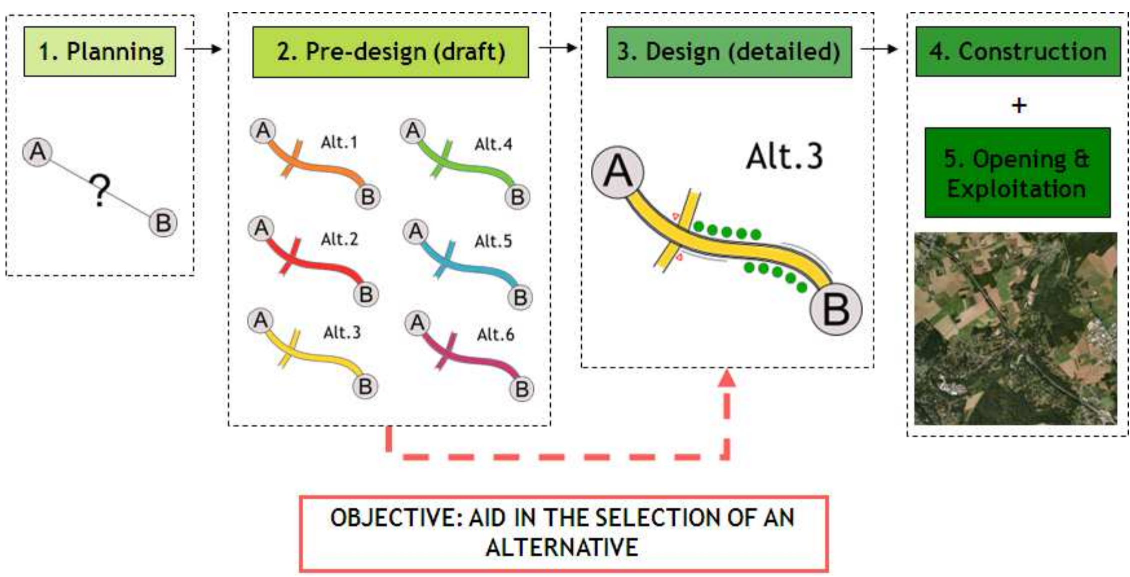

Figure 2. Design stage of an infrastructure and objective of the project

This research aims to fill that void and to offer design engineers assistance in the evaluation of their project alternatives and the identification of the best candidates. As mentioned in the previous section, this evaluation quantifies the performances of the project alternatives from a set of criteria which is composed of road safety and sustainable criteria. We propose to use this set of criteria as a representation of the concept of sustainable road safety. With the assistance of the multicriteria model, a design engineer would then be able to evaluate and to compare several alternatives of a road project. Therefore, it would be possible to select the best solution according to the characteristics of the project or the demands of the specification. In the long run, the use of integrated assessment during the design stage of road project may promote the development of innovative and sustainable solutions.

3. Multicriteria decision analysis applied to sustainable road safety

Based on the observations presented in the previous section, this research project had been initiated in 2010 to fulfill two main objectives. At first, the integration of road project evaluations into a sustainable approach by defining the concept of sustainable road safety. And secondly, the development of a multicriteria analysis methodology which would allow us to carry out an integrated and preventive assessment of infrastructure projects at the design stage.

3.1 Definition of the concept of sustainable road safety

One of the main findings of this on-going research project is the definition of the concept of sustainable road safety and its representation into quantitative criteria. From the analysis of several studies that have been conducted on the topic of road safety issues studied through the prism of the infrastructure (Gitelman and Hakker, 2006) (OECD, 1999), we define the eight following topics, spread in the dimensions Infrastructure (INF) and Services (SRV).

Table 1. Topics related to the road safety

Dimension	Code	Name
Infrastructure	INF1	Legibility and consistency of the infrastructure
Infrastructure	INF2	Visibility of the infrastructure
Infrastructure	INF3	Protection of the vulnerable roads users
Infrastructure	INF4	Quality of the road pavement materials
Infrastructure	INF5	Road design and safety equipment
Infrastructure	INF6	Intersections
Infrastructure	INF7	Safety on road works
Services	SRV1	Information and intervention services

These topics constitute the first part of the set of criteria that is used in our multicriteria methodology. They will allow us to quantify the performances of the road infrastructure projects in relation to safety.

In order to enrich the evaluation of road projects with sustainable concerns, we need to define the additional topics that would represent the concept of sustainable road safety. Over the past few years, several studies had been conducted on the topics of sustainable roads (e.g. GreenRoads, Routes durables, Grille RST02) and sustainable safety (e.g. Vision Zero, Sustainable Safety). But regarding the sustainable safety concept, these studies are exclusively focused on the social dimension of the sustainable development. As a part of this project, we have broadened the sustainability notion to the three pillars of sustainable development – economic (ECO), social (SOC) and environmental (ENVI). To illustrate the sustainability issues in our analysis, we have then selected the five following topics.

Table 2. Topics related to road sustainability

Dimension	Code	Name
Environmental	ENVI1	Reduction of greenhouse gases emissions
Environmental	ENVI2	Limitation of noise pollution
Social	SOC1	Ensure a good level of service
Economic	ECO1	Limitation of the construction costs
Economic	ECO2	Limitation of the maintenance costs

Finally, the association of all these thirteen topics (Tables 1 and 2) illustrates the concept of sustainable road safety. We are then dealing with a typical multicriteria decision aiding problem wherein the alternatives of the problem are the draft alternatives of the project at the design stage, and the criteria are the sustainable safety performances.

3.2 Structuring the multicriteria problem

In order to solve this multicriteria problem and to ensure the consistency of the model, it is important to develop a consistent set of criteria by identifying the key factors and parameters of each topic. As far as possible, even if we cannot completely avoid the subjectivity of the decision maker within the decision process, we must try to develop quantitative criteria to maximize the impartiality of the multicriteria analysis. In this study, we have developed a set of criteria by conducting an important literature review. Some meetings have been organized with experts from the road sector to criticize and validate the final set of criteria. In addition, an important stage of modelling and creation of data had been necessary to transform the initial topics – sometimes exclusively qualitative or descriptive – into quantitative criteria. This transformation would allow us to ensure a consistent and meaningful analysis.

Because of the complexity of several theoretical concepts, the developments of some criteria have been deliberately limited to a qualitative assessment. Nevertheless, these methodological strategies do not undermine the relevance of the analysis.

Hereinafter, we briefly describe the set of criteria (by referring to the five dimensions introduced in the previous section) to illustrate the multidisciplinary nature of the multicriteria problem and its complexity.

INF1. Legibility and consistency of the infrastructure

When a driver is traveling on a road, he generates a mental representation of the road which will condition his behavior on it. The driver's mental representation of the road will depend on some roadway geometric design elements such as vertical and horizontal alignments, the type of cross-section or the roadside development (OECD, 1999). In order to control the adequacy of the operating speed with regard to geometry of the road, we can measure the sight distance on each section of the road. The sight distance refers to the distance which is "required for a driver to avoid an obstacle on the road". According to the World Road Association (PIARC, 2003), there are three main types of sight distance: the stopping sight distance (or minimum sight distance), the overtaking sight distance and the manoeuvre sight distance. The stopping sight distance, denoted *DVA*, corresponds to the distance required for a driver to stop at an intersection or in front of an obstacle on the road. This distance is calculated with the 85th percentile of the speed V_i (km/h), the reaction time t (s), the coefficient of longitudinal friction f_l and the eventual percentage of the gradient G (%).

$$DVA_{op} = \frac{V_i \times t}{3,6} + \frac{V_i^2}{254\left(f_l \pm \frac{G}{100} \right)} \tag{1}$$

The measure of sight distance as a criterion to evaluate the legibility of a road has been introduced in many studies (OECD, 1999) (FHWA, 1992). Consequently, this criterion evaluates the level of legibility and consistency of the road from the measure of the stopping sight distance on the *n* sections of the road (2).

$$C_{LC} = \frac{1}{n}\sum_{i=1}^{n} Min(1; \frac{DVA_{i,op}}{DVA_{i,th}}) \tag{2}$$

In this equation, $DVA_{i,op}$ is the operating sight distance (1) and $DVA_{i,th}$ is the theoretical sight distance (i.e. minimum sight distance to ensure safety on the section i) and it is available in the literature (Harwood et al., 1995). This criterion has to be minimized.

INF2. Visibility of the infrastructure

The visibility of the road refers to the roadway elements and equipment which convey visual information to the road drivers, such as road signs, geometric design elements and road lighting. These elements could affect (positively or negatively) the global understanding of the infrastructure by the road user. Then, the aim of the criterion “Visibility” is to evaluate the influence of roadway equipment on the visual recognition of the road by the road users. The level of visibility of the road C_V is measured by summing the coefficients of visibility α_k of the m roadway elements and equipment (3). The coefficient α_k is an integer between 0 (very bad) and 10 (very good) which is attributed by the expert to each *k* roadway element. Due to the lack of information about this topic in the literature, we have determined the values of this coefficient by ourselves. By definition, this criterion has to be maximized.

$$C_V = \frac{1}{m}\sum_{k=1}^{m} \alpha_k \tag{3}$$

INF3. Protection of the Vulnerable Road Users

One of the main characteristics of a secondary rural road is its multimodal nature. Many types of users are traveling on the same road with very different speeds and mass. Thus, as a consequence of these differences among users, the risk of accidents is high on rural roads for pedestrians, bicycles and motorcycles – who are usually classified as the vulnerable road users (VRU). In 2008, on Belgian rural roads, 30% of the road killed and 34% of the severe injuries concerned vulnerable road users.

Thus, concerning the bicyclists, suitable equipment must be selected considering some factors such as the operating speed of the motorized traffic, some geometric design parameters (e.g. lane width, separation distance between the roadway and the cycle path) or the volume of traffic. On the basis of the Compatibility of Roads for Cyclists Index *CRCI* in rural areas (Noël et al, 2003) and the Pedestrian and Bicyclist Safety Indices at Intersections *P/BSII* (FHWA, 2006), we have defined a global index C_{BSI} which expresses the global level of safety of a bicycle equipment on a road (4).

$$C_{BSI} = 0.5 \cdot C_{BSI,segment} + 0.5 \cdot C_{BSI,inters} = 0.5 \cdot CRCI + 0.5 \cdot BSII \qquad (4)$$

wherein $C_{BSI,segment}$ is the CRC Index on straight segments of the road and $C_{BSI,inters}$ is the Bicycle Safety Index at intersections. These indexes are calculated by taking into account some parameters such as the average daily traffic, the speed limit, the separation distance between the roadway and the cycle lane or even some signalization factors. The value of C_{BSI} is expressed on a scale which defines the level of safety of the cycle facilities.

Concerning the pedestrians, we have defined a similar index C_{PSI} which evaluates the global level of safety of a pedestrians' equipment (straight sections and crossings). As regards motorcyclists and moped drivers, it is important to pay attention to the slippery surfaces or road markings and to the roadside safety barriers (OECD, 1999). However, due to the lack of information about this topic in the literature, we have not included this category of VRU in the criterion for the moment.

Then, we define the criterion C_{VRU} which expresses the global level of safety for vulnerable road users on the road based on the indexes C_{BSI} and C_{PSI} defined above (5). The actual weights have been defined on the basis of the probabilities of accidents of pedestrians and bicyclists on rural roads in Belgium in 2012 (DGSIE, 2013).

$$C_{VRU} = 0.52 \cdot C_{BSI} + 0.48 \cdot C_{PSI} \qquad (5)$$

INF4. Quality of the road pavement materials

A poor road surface quality can result in a loss of control of the vehicle (e.g. skidding). Combined with the high speeds on rural roads, these structural defects can lead to highly severe accidents. Consequently, it is very important to preserve the quality of the road surface. On the basis on some researches about the development of performance indicators for the selection of road pavements (COST, 2008) (BRRC, 2006), we can define a safety index for the road surface C_{RS}. This index is calculated with some performance indicators about the transverse evenness PI_R, the skid resistance PI_F, the drainability PI_D and the sensitivity to winter conditions PI_{WC}.

$$C_{RS} = 0.45 \cdot \left(0.7 \cdot PI_R + 0.3 \cdot PI_D\right) + 0.4 \cdot PI_F + 0.15 \cdot PI_{WC} \qquad (6)$$

The actual weighting has been defined on the basis of some research from COST and BRRC. However, a sensitivity analysis will be conducted on these weights at the end of the calculation process in order to ensure their robustness. The performance indicators are common values stored in our model for several road pavement materials. This criterion must be minimized.

INF5. Road design and safety equipment

According to the Belgian Institute for Road Safety, run-off accidents represent around 32% of all fatal rural accidents on Belgian rural roads. Then, if we cannot totally avoid this type of accidents, we can reduce their severity by installing some safety equipment along the infrastructure. Thus, the criterion "Road design and safety equipment" evaluates the performance of the infrastructure regarding to its geometry, the environment and the safety equipment (e.g. vehicle restraint systems). The evaluation is based on a prediction model from the Highway Safety Research Center which measures a predictive accident rate from several parameters such as the lane width, the shoulder width or the roadside safety (Zegeer et al., 1994).

$$C_{SE} = c_0 \cdot AADT^{c1} \cdot c_2^{\ LW} \cdot c_3^{\ PS} \cdot c_4^{\ UP} \cdot c_5^{\ RS} \cdot c_6^{\ TER1} \cdot c_7^{\ TER2} \qquad (7)$$

In (7), c_i are model parameters adapted to the Belgian road network context, *AADT* is the annual average daily traffic, *LW* is the lane width, *PS* is the width of paved shoulders, *UP* is the width of unpaved shoulders, *RS* is the roadside safety coefficient and *TER* are variables related to the roadway environment. Given that this criterion measures a predictive accident rate, it must be minimized.

INF6. Intersections

This criterion quantifies the consistency of the intersections of the project with the function of the road, the volume and the composition of the traffic, the operating speed and some others characteristics of the project. Depending on the type of intersection, we compare the time which is necessary to realize different manoeuvres in the crossroads with the minimum time that is required to ensure safety conditions to the users. In practice, we evaluate this global required time to manoeuvre by calculating the operating traffic capacity at the intersection.

INF7. Safety on road works

This last criterion of the dimension infrastructure refers to the protection of workers and road users during reconstruction or maintenance activities. Indeed, during these road works, the normal traffic situation is disrupted and this could affect the safety around the work zones. Then, based on methodology that have been developed for the European project STARs about the safety on road works (Weekley et al., TRA2014), we measure a road worker safety risk score. To date, the calculation procedure of this criterion is confidential because the STARs project is still an on-going research.

SRV1 – Information and intervention services

This criterion has been developed to take into account the quality of the information and the intervention services in the evaluation of the road safety performances of a project alternative. However, because of the lack of knowledge and information in this research area, no pertinent criterion has been defined yet. To date, this criterion is a descriptive scale that ranks the quality of services regarding to the type of service equipment available (e.g. emergency call terminal, clear zone or emergency lane along the road, safety camera, etc.).

ENVI1 – Reducing greenhouse gases emissions

The restriction of the greenhouse gases emissions is one of the most frequently used criteria to represent environmental concerns. The criterion C_{GHG} measures the annual average concentration of PM_{10} (c_{PM}) and NO_2 (c_{NO}) generated by a road project. The values of concentration depend on the traffic volume and composition, some emission factors, the direct environment of the road, the operating speed and the roadway surface.

While we have calculated the values of annual average concentration of PM_{10} and NO_2, we normalize these values on a scale from 0 to 5. This normalization is based on the minimum, maximum and thresholds values of concentration in Belgium measured every year by the Belgian Interregional Environment Agency. From there, we calculate a weighted sum (8) wherein the weights of the normalized evaluation of concentration $|c_{PM}|$ and $|c_{NO}|$ are respectively the evaluation of $|c_{NO}|$ and $|c_{PM}|$. This criterion must be minimized.

$$C_{GHG} = \frac{|c_{PM}|^2 + |c_{NO}|^2}{|c_{PM}| + |c_{NO}|} \tag{8}$$

ENVI2 – Limitation of noise pollution

The noise pollution refers to the noise generated by the vehicular traffic on the roadway. The intensity of the noise depends on the characteristics of the vehicles (e.g. motor and tire types), the roadway surface type, the operating speed and some geometric design parameters. Then, if the evaluation of the "operating" noise pollution is very complex and requires the development of computer models, many studies have been interested in the definition of simplest evaluation of noise pollution. In Switzerland, a project of the Federal Office for the Environment had led to the development of a model which calculates the noise pollution generated by a road infrastructure (OFEFP, 1995). This evaluation is based on the characteristics of the infrastructure such as the traffic density and composition, the speed limit, the nature of road surface material or even the nature of the roadside environment (9). Then, this value is compared to the limit values for noise pollution (or acceptable values with regards to comfort and health) which have been defined by the noise pollution standards.

$$L = A + 10 \cdot \log\left[\left(1 + \left(\frac{v}{50}\right)^3\right) + \left(1 + B \cdot Eta \cdot \left(1 - \frac{v}{150}\right)\right)\right] + 10 \cdot \log(M) + \Delta R \tag{9}$$

In (9), A is a coefficient depending on the road pavement material, B is an empirical constant, v is the operating speed, M is the traffic low (vehicles by hour), *Eta* is the proportion of heavy trucks and ΔR is a corrective coefficient for noise reflections (depending on geometric data such as the width of the roadway, the height of the potential buildings, etc.). The level of noise L is measured in dB(A). It can be applied for daytime (Ld), evening time (Le) or night time noise (Ln). Thus, the criterion "*Noise pollution*" calculates the level of noise generated by the infrastructure during night time, day time and evening time by referring to the Ln and Lden indices (10). The level Lden is calculated as follows.

$$Lden = 10 \cdot \log 10\left[\frac{\left(12 \cdot 10^{\frac{Ld}{10}} + 3 \cdot 10^{\frac{Le+5}{10}} + 9 \cdot 10^{\frac{Ln+10}{10}}\right)}{24}\right] \tag{10}$$

The values Ln (11) and Lden (12) in dB(A) are normalized on a scale from 0 to 5.

$$|Ln| = \begin{cases} 0 \text{ if } Ln \prec 30 \\ 2.5 \cdot \frac{Ln}{30} - 2.5 \text{ if } 30 \le Ln \prec 60 \\ 2.5 \cdot \frac{Ln}{50} - 0.5 \text{ if } 60 \le Ln \prec 110 \\ 5 \text{ if } Ln \succ 110 \end{cases} \tag{11}$$

$$|Lden| = \begin{cases} 0 \text{ if } Lden \prec 30 \\ 5 \cdot \dfrac{Lden}{80} - 1.875 \text{ if } 30 \le Ln \prec 110 \\ 5 \text{ if } Ln \succ 110 \end{cases} \qquad (12)$$

Finally, we obtain the criterion C_{NP} which must be minimized (13).

$$C_{NP} = \frac{|Ln|^2 + |Lden|^2}{Ln + Lden} \qquad (13)$$

SOC1. Ensure a good level of service
In order to take into account the social aspect of a road project in the multicriteria evaluation, we have decided to consider the level of service of the infrastructure. Indeed, guarantying a good mobility and accessibility on the road infrastructure is an important element with regard to the social performance of a road project. Then, based on the developments from the Highway Capacity Manual (TRB, 2010b), we assess the quality of service provided by the road infrastructure by measuring its level of service (LOS).
According to the Transportation Research Board, level of service is a "quantitative stratification of a performance measure or measures that represent quality of service [the operational performance of the infrastructure from the traveler's perspective]" (TRB, 2010a). Considering the theoretical traffic capacity of the infrastructure (which depends on parameters such as the number of lanes, the type of intersection, the speed limit, etc.) and the predictive traffic flows, the criterion "*Ensure a good level of service*" measures the level of service of the infrastructure on an ordinal scale from A to F (14).

ECO1. Limitation of construction costs
This criterion enables the decision maker to evaluate the economic performance of a road project simply by calculating the construction costs. However, considering that it is complex to obtain detailed and updated economic data about road projects in Belgium (mainly due to some confidential issues), the evaluation of this criterion remains quite vague for the moment. This criterion is expressed in euros and must be minimized.

ECO2. Limitation of maintenance costs
This criterion is very similar to ECO1, except that it evaluates the maintenance costs. This criterion is expressed in euros and must be minimized.

3.3 Case study

Once a complete set of criteria has been developed, the next step is to identify all the efficient solutions. The efficient solutions could be defined as the best candidates to solve the problem. From a theoretical point of view, a solution S_i is called efficient if there is no solution S_j in the set such that S_j is at least as good as S_i on all the criteria and strictly better for at least one of them. As introduced previously, the aim of this study is to help engineers in the evaluation and the selection of design road project alternatives. In the following section, we propose to

use the set of criteria developed previously on an illustrative case study in order to prove the interest of this multicriteria approach and to underline the type of results we may obtain.
This case study concerns the redevelopment of a secondary road in a rural area with a multimodal traffic (Table 3). In the following example, we will consider a limited set of 10 alternatives to ensure the readability and the global understanding of the multicriteria approach. However, for a real case study, we define all the feasible alternatives of the problem by a combination of parameters to ensure an exhaustive analysis of the design space. In addition, we will consider a limited set of 6 criteria due to the nature of the case study. A simplified version of the criterion “Intersection” has been used.

Table 3. Description of the case study

Parameter	Value
Area	Rural
Function of the road	Secondary road
Length	2.0 km
Maximum width	12 m
Number of intersections	2
Traffic volume (AADT)	2500 veh/day
Fraction of heavy vehicles	10%
Presence of cyclists	Yes
Presence of pedestrians	No
Presence of obstacles	Yes (trees along the roadway)

Based on the characteristics of the road project and its direct environment, we have designed 10 different draft alternatives (cf. Appendices) by modifying some design parameters such as the number of lanes, the width of the lanes and shoulders, the nature and width of the cycle path, the speed limit, the nature of the safety equipment and the type of intersections. To limit the size of the problem, we have considered the same road surface material and the same road signing, marking and lighting equipment for every alternative. We have then calculated their evaluation on each criterion of the set (Table 4).

Table 4. Evaluation table of the multicriteria problem

Alt.	INF3 VRU	INF5 Design	INF6 Intersections	ENVI1 Greenhouse	ENVI2 Noise	ECO1 Costs
A1	22	0,32377	3	4,2681	2,8531	180650,00
A2	17	0,20706	1	4,2722	2,8531	618850,00
A3	27	0,32377	3	4,2681	2,9249	180970,00
A4	37	0,59814	1	4,2681	2,8531	1121500,00
A5	62	0,56184	3	4,255	2,8531	95474,00
A6	27	0,23072	2	4,2704	2,9249	1186600,00
A7	27	0,56337	2	4,2722	2,8531	1125800,00
A8	42	0,23072	3	4,2704	3,022	217150,00
A9	30	0,75205	2	4,2798	2,8531	281700,00
A10	50	0,7749	1	4,279	2,8531	279620,00

Then, if we consider an equal distribution of the weights among the criteria (i.e. 16.7% each), we can generate a multicriteria ranking of the alternatives by using the net flow scores of the outranking method PROMETHEE II (Vincke, 1989). This method is based on pairwise comparisons of the evaluations of the alternatives and the representation of the preference and indifference with the assistance of preference functions. In this example, we have chosen usual preference functions for the criteria INF6, ENVI1 and ENVI2. We have defined U-shape preference functions for the criteria INF3 (q=0.05) and INF5 (q=5). And we have defined a linear preference function for the criterion ECO1 (q=5000, p=10000). We have used the D-SIGHT software to generate the ranking on Figure 3 (Hayez et al., 2012).

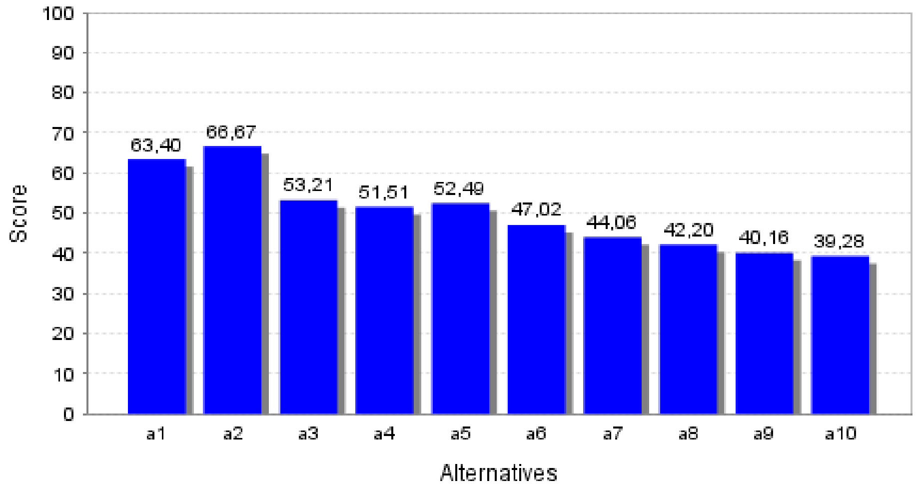

Figure 3. Ranking of the alternatives based on PROMETHEE II net flow scores

The previous figure represents the ranking of the solutions based on the PROMETHEE II net flow scores. The alternatives a1 and a2 are the preferred solutions of the problem according to the preferences of the decision maker. The Table 5 represents the stability of the alternative a2 as the first ranked solution of the problem. Based on the stability intervals of each criterion, we can observe that the alternative a2 is highly robust. Indeed, we need to modify the weights significantly to change the position of the alternative a2 in the ranking.

Table 5. Stability intervals for the first ranked alternative

Criteria	Min Weight	Value	Max Weight
INF3	2.0%	16.7%	100%
INF5	5.6%	16.7%	100%
INF6	12.7%	16.7%	100%
ENVI1	0.0%	16.7%	21.8%
ENVI2	0.0%	16.7%	100%
ECO1	0.0%	16.7%	22.1%

In addition, we may use a global visualization tool given by the GAIA plane to analyse more precisely the characteristics of the problem and the nature of the solutions. The Figure 4 represents the plane obtained after applying a principal components analysis to the alternatives of the problem. Due to the projection, there is a small loss of information (about 28% here) but the study of the GAIA plane still leads to interesting observations. At first, we may notice that alternative a2 performs well in the criteria INF2, INF5 and INF6 while it obtains quite bad evaluations on the other criteria. At the contrary, the alternative a5 performs very well on the economic and environmental criteria but suffers from bad evaluations on the criteria related to the infrastructure performances. In addition, the ranking on the Figure 3 shows that the alternatives a1 and a2 obtain a similar net flow score. However, the analysis of the GAIA plane points out that their profiles are quite different.

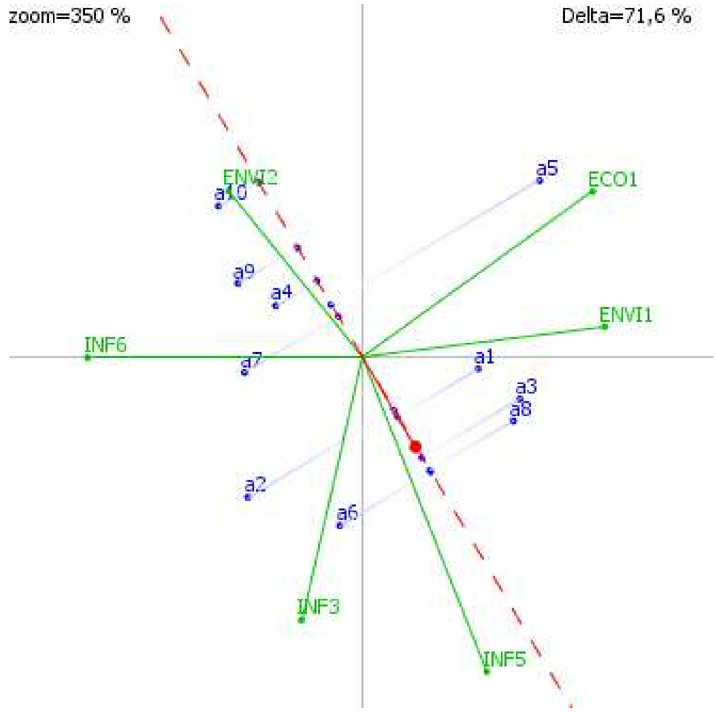

Figure 4. Visual representation of the problem on the GAIA plane

4. Current and future developments

Considering that the actions are defined a priori by combinations of parameters (e.g. number of lanes, width of lanes, roadway materials, type of cycle equipment, type of safety equipment, type of lighting equipment, etc.), the size of the problem may rapidly become important. As an example, Table 6 shows that even a very simplified case study with only 12 input parameters (ranging from 2 to 5 values each, except *cp_nat*) generates more than 10^6 feasible alternatives. Then, considering the large number of alternatives and criteria of our problem, the exhaustive enumerations of all the solutions would imply an important calculation time. Therefore, we have decided to apply a metaheuristic to address this issue.

Table 6. Amount of alternatives for a simplified problem

Variable	Value	Description
w_max	14	maximum available witdh (fixed parameter)
w_l	{2,5;3;3,5}	roadway lane width
n_l	{2;3;4}	number of lanes
w_sh	{0;1;2;3}	shoulder width
b_sh	{Y;N}	physical separation with shoulders (e.g. barriers)
cp_nat	[1:17]	type of bicyclist equipment
w_med	{Y;N}	physical separation between flow and contraflow
mat_nat	{1;2;3;4;5}	type of road surface material
rsign	{1;2}	nature of the signalization equipment
marking	{1;2}	nature of the marking equipment
lighting	{0;1;2;3}	nature of the lighting equipment
intertype	{1;2;3;4}	type of intersection
v	{50;70;90}	speed limit
alt	**1000320**	**amount of feasible alternatives**

In this research project, we have used the multi-objective evolutionary algorithm NSGA-II (Deb, 2002). This algorithm is a metaheuristic that is able to deal with large problem and to find solutions with a high convergence speed. From the complete set of alternatives, we randomly select a limited sample of alternatives that constitutes the initial population. We generate the evaluation table of this initial population and then, we identify the non-dominated solutions. We start the genetic process and we improve the quality of the initial solutions by applying crossover and mutation operations on each successive set of solutions. At the end, the set of solutions has converged and the set of non-dominated solutions of our problem has been identified.

Table 7. Amount of Pareto solutions obtained after NSGA-II (150 generations)

Variable	Value	Description
Alt	1000320	Total amount of feasible alternatives
initial_pop	150	Size of the initial population for NSGA-II
Gen	150	Number of generations in NSGA-II
pareto_sol	**61**	**amount of pareto solutions**

The Table 7 contains the results of the simplified problem introduced previously after using NSGA-II. The initial population was composed of 150 alternatives randomly selected and 150 generations have been conducted in NSGA-II. At the end of the process, 61 non-dominated (or Pareto) solutions have been identified.

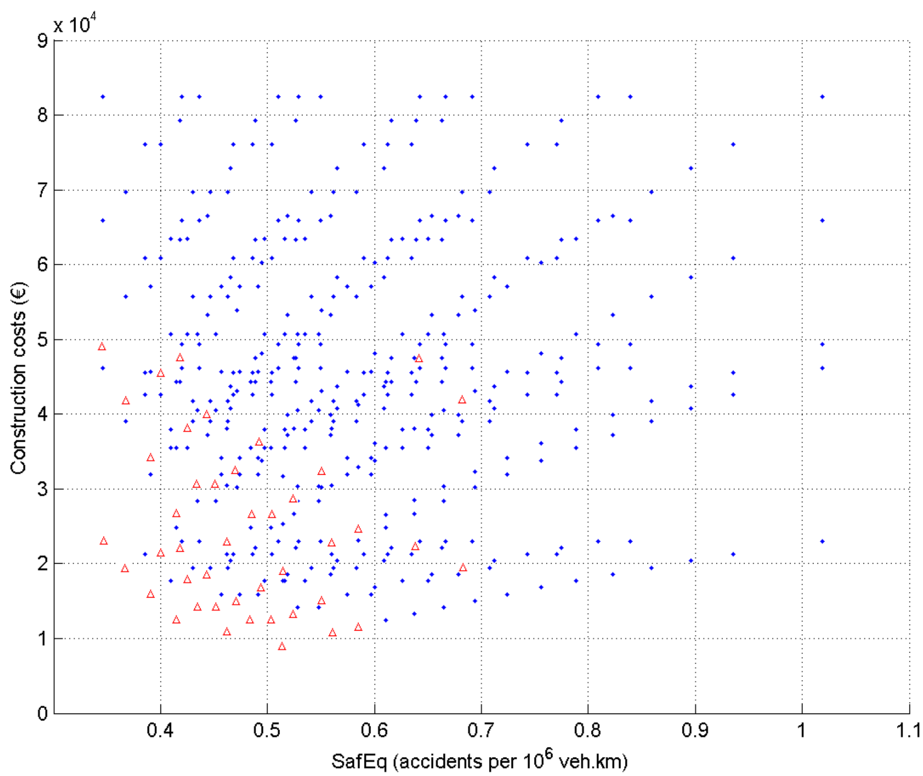

Figure 5. 2-axis projection view of the dominated and non-dominated solutions

The Figure 5 shows a projection view on the objectives "*ECO1. Reduction of constructions costs*" and "*INF5. Road design and safety equipment*" of the initial population (blue dots) and the non-dominated solutions (red triangles). These interesting results illustrate the utility of using a multi-objective evolutionary algorithm, given that it proceeds to an efficient and extensive design space exploration.

This heuristic allows us to consider several criteria at the same time and then to give relevant information to the decision maker. For example, if we consider the closest triangles to the axis of the Figure 5, we observe that a small gain on the criterion *SafEq* from 0.5 to 0.35 accidents per 10^6 veh.km implies an increase of the *Costs* from 9000€ to 22000€.

Once the Pareto frontier has been identified, we may analysis the quality of the solutions and the performance of the NSGA-II algorithm by using performance indicators available in the literature. By instance, we may evaluate the density and diversity of the solutions which compose the frontier (e.g. spread, binary hypervolume indicator), and the convergence of the algorithm (e.g. contribution, binary ε-indicator, binary hypervolume indicator) (Talbi, 2009).

Finally, we may use a complementary methodology to solve the multicriteria problem. However, a detailed analysis of this solving process goes beyond the scope of this paper.

5. Conclusion and further developments

In this study, we have developed an innovative model to assess both the road safety and the sustainable performances of a project at the design stage. Considering the objectives of the EU to reduce the number of fatalities on the road network by 2020, we have initiated the development of a preventive approach based on the concept of sustainable road safety. In addition, we have decided to use a multicriteria decision aiding methodology to assist the engineers during the design process of an infrastructure. At the pre-design stage of the process, we generate all the feasible alternatives of the project – by generating parameter combinations and we support the engineers in the evaluation and the selection of the best solutions for a specific road infrastructure problem by using a multicriteria model. This model is based on the NSGA-II algorithm.

To date, the first results of this on-going research are promising and due to its multidisciplinary nature, the use of a multicriteria methodology seems fully relevant. In the short term, we will focus on the study of the set of non-dominated solutions which constitute the Pareto frontier and the final solving of the problem.

In the long run, the use of this model may lead to the definition of innovative and integrated solutions. Additionally, the improvement of the set of criteria may help us to have a better understanding of the road safety issues and them quantification.

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Appendices

Hereinafter, we describe the alternatives of the case study. The variables have been defined previously in the Table 6.

Table A1. Alternatives of the case study

Variable	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10
w_l	2.5	3.5	2.5	3	2.5	3	3	3	3.5	3.5
n_l	2	2	2	2	2	2	2	2	4	4
w_sh	2	3	2	0	0	2.5	1	3	0	0.5
b_sh	0	0	0	1	0	0	0	0	0	0
cp_nat	6	7	6	2	3	8	2	6	6	3
intertype	2	3	1	3	2	4	4	2	4	3
v	50	50	70	50	50	70	50	90	50	50

intertype: {1;2;3;4} = {give way to right; through road; traffic signals; roundabout}
cp_nat: {2} = marked cycle lane on the road – width = 1m
{3} = shared lane (mixed traffic)
{6} = separated cycle lane – width = 1,5m – no separation
{7} = separated cycle lane – width = 1,5m – delineators
{8} = separated cycle lane – width = 1,5m – barriers

Below, we show the results of the PROMETHEE II analysis. The global net flow score is calculated by subtracting the positive to the negative net flow score.

Table A2. PROMETHEE II net flow scores

Alternatives	Rank	Net flow	Flow+	Flow-
a1	2	0.2680885	0.4689025	0.200814
a2	1	0.3333333	0.5555556	0.2222222
a3	3	0.0641977	0.4132222	0.3490246
a4	5	0.0302339	0.3820858	0.3518519
a5	4	0.0498386	0.420209	0.3703704
a6	6	-0.0596296	0.3703704	0.4300000
a7	7	-0.1187524	0.288655	0.4074074
a8	8	-0.1560741	0.3376257	0.4936998
a9	9	-0.1967934	0.2777778	0.4745712
a10	10	-0.2144425	0.2962963	0.5107388