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Design safer and greener road projects by using a multi-objective evolutionary approach

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(*submitted in June 2014*)

Over the past few years, both recognizing sustainable development and improving road safety have been main issues in policies for transport and mobility in Europe. Since 2001, the European Commission had published several reports about the improvement of the level of safety and sustainability on the European road network. However, few tools or methodologies have been developed to support actively the road sector in the design of safer and greener roads. Consequently, this research project aims to develop a multicriteria analysis methodology to carry out an integrated and preventive assessment of the road safety performances and the sustainable aspects of road projects at the design stage. Due to the combinatorial nature of design projects, we have investigated how an evolutionary approach, such as NSGA-II, could help the engineers to identify efficient alternatives. The algorithm is studied by means of well-known performance indicators.

Keywords: multi-objective optimization, NSGA-II; performance indicators; sustainability; road safety;

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 (EC 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 (EC 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 2008, 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 (EC 2008).

In Belgium, the Federal Commission for the Road Safety had been formed in 2002 with intent to fulfill the EC objectives. 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,

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seatbelt, alcohol and driving, etc.) (IBSR 2012). 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 (Walloon Region 2009).

However, it has become essential to take more practical and effective actions to meet these objectives of improving road safety and considering more significantly the sustainable character of the road transport infrastructure. In particular, we should develop new preventive and innovative tools which may be used during the design stage to assess the technical and sustainable performances of a project. In the long run, these tools would allow us to design innovative road infrastructure projects and to promote solutions more consistent with the sustainable transport policies.

But 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. Moreover, the selection of project alternatives at the design stage is still mainly motivated by the economic aspect while the environmental and the social aspects are often neglected. Based on these observations, we have initiated the development of a preventive analysis of the sustainable and safety performances of a road project at the design stage.

The structure of this paper is as follows. We start with a description of the research questions where we briefly discuss about the evaluation of road safety and the integration of sustainability assessment in the design process of a road project. Next, we introduce the concept of sustainable road safety which structures our multicriteria methodology. Thereafter, we outline the method used. We introduce the problem and the genetic algorithm. Then, we present the results by analyzing several performance indicators. We finish with a discussion and some conclusions.

2. Research questions and motivation

2.1 *Towards a preventive evaluation of road safety*

In 2013, the level of safety on the Belgian roads had slightly improved with a global decrease of the number of road deaths by 5.8%. This reduction corresponds to a total of 720 road deaths and it is in accordance with the objectives of the EC of decreasing to 620 road deaths in 2015 and 420 in 2020. However, when comparing with the situation in France (-11%) and Germany (-10%), the decrease is slower in Belgium (IBSR 2013). Therefore, to accentuate the improvement of road safety in Belgium and to maintain this orientation in the long run, it would be relevant to assess preventively the safety performances of a road project during the design stage.

At first, it is important to define theoretically what road safety is. To do so, we can use the elementary triangle of road safety (Figure 1) 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.

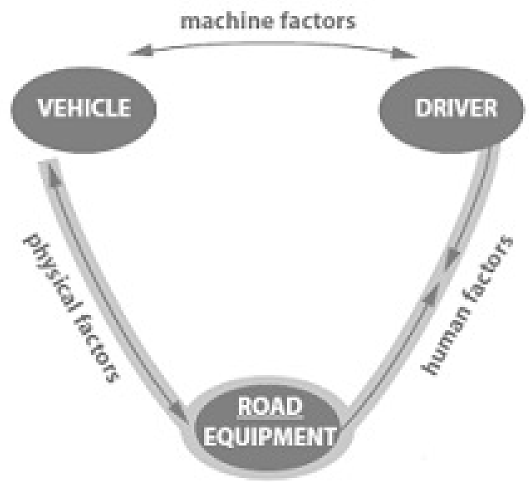

Figure 1. Elementary triangle of road safety

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 infrastructures have close links with some sustainable topics such as energy consumption (EEA 2011), preservation of environment, economic performance, noise disturbance (OFEFP 1995; den Boer and Schroten 2007) or even social impact (SETRA 2008). In practice, it both implies to reconsider current policies by taking into account more precisely 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 previously, several reports have been published during the past years by national and European organizations in order to promote sustainable roads. However, there is still a lack of tools and processes that could assist the actors of the road sector in the practical and integrated evaluation of the sustainable performances of their projects.

In this research project, we aim to enrich the evaluation of the safety performances 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 (Figure 2). 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.

This research aims to fill that void and to offer design engineers assistance in the

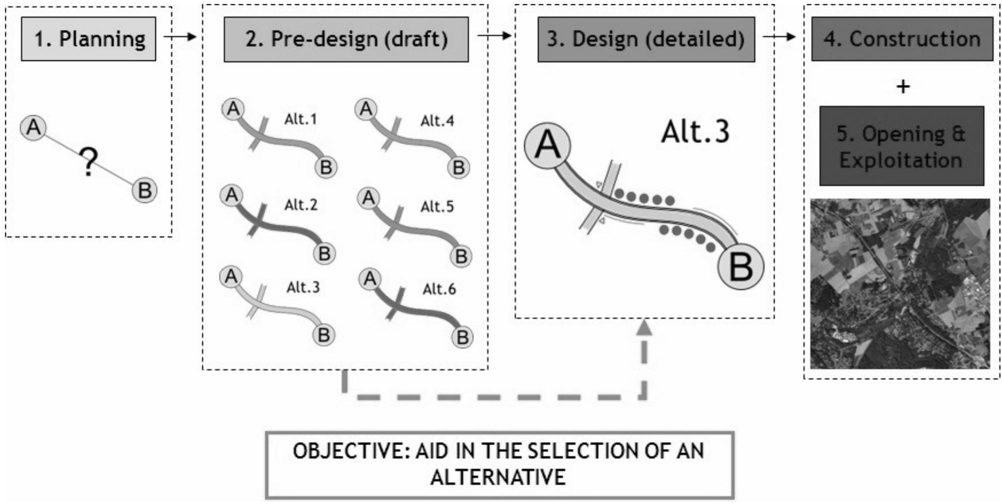

Figure 2. Design stage of an infrastructure and lack of support in the selection process

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. This set represents the sustainable road safety.

By using this model, a design engineer would be able to evaluate and to compare several alternatives of a road project based on their technical, economic, environmental and social performances. 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. Structuring the multicriteria decision aiding problem

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 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. At first, we have conducted a large literature review on the topic of road safety (OECD 1999; Gitelman and Hakker 2006). In particular, we were focusing on the safety issues or characteristics related to the road infrastructure. Then, we have defined from this analysis the eight following topics, spread in the dimensions Infrastructure (INF) and Services (SRV).

INF1 Legibility and consistency of the infrastructure
INF2 Visibility of the infrastructure

INF3 Protection of the vulnerable roads users (VRU)
INF4 Quality of the road pavement materials
INF5 Road design and safety equipment
INF6 Intersections
INF7 Safety on road works
SRV1 Information and intervention services

These topics constitute the first part of the set of criteria that is used in our multicriteria analysis methodology. They will allow us to quantify the performance of the road infrastructure projects in relation to safety. Then, we define additional topics to enrich the evaluation of road projects with sustainable concerns. Over the past few years, several studies had been conducted on the topics of sustainable roads (e.g. Greenroads (2013), Routes durables (Nossent 2011), Grille RST02 (Boutefeu 2008)) and sustainable safety (e.g. Vision Zero (Tingvall and Haworth 1999), Sustainable Safety (Aarts and Wegman 2006)). But regarding the sustainable safety concept, these studies are exclusively focused on the social dimension of the sustainable development. As 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.

ENVI1 Reduction of greenhouse gases emissions
ENVI2 Limitation of noise pollution
SOC1 Ensure mobility of all
ECO1 Limitation of the construction costs
ECO2 Limitation of the maintenance costs

To our point of view, the association of all these 13 topics illustrates the concept of sustainable road safety. And due to the multidisciplinary nature of the concept of sustainable road safety, we are dealing with a typical multicriteria decision aiding problem wherein the alternatives of the problem are the draft alternatives of the road project at the design stage, and the criteria are the sustainable safety performances.

3.2 *Modelling of the multicriteria problem*

In order to ensure the consistency of the multicriteria evaluation model, it is important to develop a complete set of criteria by identifying the key factors and parameters of each topic. As far as possible, we must try to develop quantitative criteria to limit the subjectivity of the decision maker during the calculation process. In this study, we have developed the set of criteria by conducting an important literature review on topics related to the legibility of the road infrastructure (OECD 1999; PIARC 2004; FHWA 1992), the protection of vulnerable road users (OECD 1999; Noël, Leclerc and Lee-Gosselin 2003; FHWA 2006), the quality of road pavement materials (COST 2008; BRRC 2006), the impact of road layout and equipment (Zegeer et. al 1994), the design of intersections (FHWA 1992), the safety on road works and some others sustainable concerns. Additionally, some meetings have been organized with experts from the road sector to criticize and validate the final set of criteria.

To define these criteria, 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 which ensure a consistent and meaningful analysis. Given the complexity of some practical phenomena or theoretical concepts associated with these topics, the final criteria are of a different nature (quantitative or qualitative, ordinal or cardinal scales, etc.). In addition, the developments of some criteria have been deliberately limited to a qualitative assessment, mainly due to lack of references in the literature. Nevertheless, if some improvements may still be done in the future, the quantitative nature of these criteria does not undermine the relevance and the overall consistency of the analysis.

The exhaustive definition of the full set of criteria had been done in previous articles (Sarrazin and De Smet 2011, 2014) and it goes beyond the scope of this paper. However, to ensure the global understanding of the methodology, we briefly introduce in the following the mathematical expression of eight criteria. They are the ones we have used in the illustrative example of this paper.

3.2.1 Visibility (INF2)

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 (1). 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.

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

3.2.2 Protection of the Vulnerable Road Users (INF3)

To assess the global level of safety for vulnerable road users on the road, we calculate the Compatibility of Roads for Cyclists Index CRCI in rural areas (Noël, Leclerc and Lee-Gosselin 2003). This index measures the global level of safety of bicycle equipment on a road by summing the individual scores of several components of the infrastructure, such as the speed limit on the roadway, the dimension of the cycling space, the motorized and heavy truck traffic flows or the roadside condition. It is composed of an index base $CRCI_{base}$ and of an optional part $CRCI_{options}$.

$$CRCI = CRCI_{base} - CRCI_{options} \tag{2}$$

3.2.3 Quality of the road pavement materials (INF4)

Based on researches about the development of performance indicators for the selection of road pavements (COST 2008; BRRC 2006), we have defined 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}.

$$C_{RS} = 0.45 \times (0.7 \times PI_R + 0.3 \times PI_D) + 0.4 \times PI_F + 0.15 \times PI_{WC} \tag{3}$$

3.2.4 Road design and safety equipment (INF5)

We evaluate the performance of the infrastructure C_{SE} 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).

$$C_{SE} = c_0 \times AADT^{c_1} \times c_2^{LW} \times c_3^{PS} \times c_4^{UP} \times c_5^{RS} \times c_6^{TER1} \times c_7^{TER2} \tag{4}$$

In (4), 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 $TER_{1,2}$ are variables related to the roadway environment.

3.2.5 Intersections (INF6)

We measure the consistency and the adequacy of the intersections C_{INT} depending on the speed limit on the road infrastructure v, the function of the roads crossing at the intersection F_k and the environment δ_e (5). We identify three levels of performance for the n intersections of the project: consistent, moderately consistent and badly consistent to inconsistent corresponding to the values $\{1, 2, 3\}$. These levels have been defined for each type of intersection based on the research of Agentschap Wegen en Verkeer on the intersections (Rouffaert 2009).

$$C_{INT} = \frac{1}{n} \sum_{i=1}^{n} f_i(v, F_k, \delta_e) \tag{5}$$

3.2.6 Reduction of the greenhouse gases emissions (ENVI1)

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 wherein the weights of the normalized evaluation of concentration $|c_{PM}|$ and $|c_{NO}|$ are respectively the evaluation of $|c_{NO}|$ and $|c_{PM}|$ (6).

$$C_{GHG} = \frac{|c_{PM}|^2 + |c_{NO}|^2}{|c_{PM}| + |c_{NO}|} \tag{6}$$

3.2.7 Limitation of noise pollution (ENVI2)

We use 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 (7). 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.

$$L = A \times log\left[\left(1 + \left(\frac{v}{50}\right)^3\right) + \left(1 + B \times Eta \times \left(1 - \frac{v}{150}\right)\right)\right] + 10 \times log\,(M) + \Delta R \tag{7}$$

In (7), 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, this criterion C_{NP} 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 (8).

$$C_N P = \frac{|L_n|^2 + |L_{den}|^2}{L_n + L_{den}} \tag{8}$$

3.2.8 Limitation of construction costs (ECO1)

We simply measure the global construction costs C_{CC} by summing the costs for each equipment and materials p_k (9).

$$C_{CC} = \sum_{k=1}^{m} p_k \tag{9}$$

4. Implementation of the evolutionary algorithm

4.1 *Nature of the problem*

Once a complete set of criteria has been developed, the next step is to identify all efficient solutions of the problem. As introduced previously, the aim of this study is to help engineers in the evaluation step and the selection of road project alternatives at the design stage. Considering that the actions are defined a priori by different combinations of the design parameters of the project, the size of the problem may rapidly become important. As an example, Table 1 illustrates the number of feasible alternatives that could be generated (about 2×10^6) for a very simplified case study with only 12 input parameters (ranging from 2 to 5 values each, except cp_nat). Then, considering the large number of alternatives and criteria, the exhaustive enumerations of all the solutions would imply an important calculation time. As a consequence of this observation and due to the non linear nature of the criteria, we decided to apply a metaheuristic to address this issue.

4.2 *Implementation of the NSGA-II algorithm*

4.2.1 Structure of the NSGA-II algorithm

In this research project, we decided to use the multi-objective evolutionary algorithm NSGA-II (Deb et al. 2002). The main steps of this algorithm are as follows. From the complete set of alternatives, we randomly select a limited sample of alternatives that constitutes the initial population. Next, we generate the evaluation table of this initial population and then, we identify the nondominated solutions. Afterwards, 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 nondominated solutions of our problem has been identified.

Table 1. Total amount of alternatives for a simplified problem.

Variables	Values	Description
w_max	14	maximum available width[a]
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
tot_alt	**2350080**	**amount of feasible alternatives**

[a]This parameter is fixed.

During the genetic process, we select two parents in the current population by using binary tournament selection based on the rank and the crowding distance. When comparing two individuals, we select the one with the smaller rank or with the greater crowding distance. Then, we allow the parents to make a crossover with a probability P_c of 90%. We use *Simulated Binary Crossover* to generate new individuals (Deb and Agarwal 1995) :

$$\begin{aligned} c_{1,k} &= 0.5 \times \left[(1-\beta_k)\, p_{1,k} + (1+\beta_k)\, p_{2,k} \right] \\ c_{2,k} &= 0.5 \times \left[(1+\beta_k)\, p_{1,k} + (1-\beta_k)\, p_{2,k} \right] \end{aligned} \tag{10}$$

where β_k (≥ 0) is a spread factor, $c_{i,k}$ (resp. $p_{i,k}$) is the evaluation of the i^{th} child (resp. parent) on the k^{th} objective.

Then, we allow the individuals of the child population to mutate with a probability P_m of 30%. We use a polynomial mutation to generate the offspring c_i'.

$$c_i' = c_i + \left(c_i^u - c_i^l \right) \delta_i \tag{11}$$

where c_i^u (resp. c_i^l) is the upper (resp. lower) bound of the individuals c_i and δ_i is a parameter computed from a polynomial probability distribution (Taalbi 2009). In the following equation, η_m is the distribution index and r_i is a random number between 0 and 1:

$$\begin{aligned} &P(\delta) = 0.5 \times (\eta_m + 1)\left(1 - |\delta|^{\eta_m}\right) \\ &\delta_i = \begin{cases} (2r_i)^{\frac{1}{\eta_m+1}} - 1 & \text{if } r_i < 0.5 \\ 1 - \left(2\,(1-r_i)\right)^{\frac{1}{\eta_m+1}} & \text{otherwise} \end{cases} \end{aligned} \tag{12}$$

4.2.2 Results of the simplified problem

The Table 2 contains the results of the simplified problem introduced previously after using NSGA-II. The initial population was composed of 50 alternatives randomly selected and 50 generations have been conducted in NSGA-II. A limited set of 8 criteria has been considered. At the end of the process, 178 nondominated (or Pareto) solutions have been identified. This value corresponds to the average value after 30 runs of the NSGA-II algorithm.

Table 2. Amount of Pareto solutions obtained after NSGA-II (w_max = 14m ; 50 gen ; 30 tests)

Variables	Values	Description
alt	2350080	Total amount of feasible alternatives
initial_pop	50	Size of the initial population for NSGA-II
gen	50	Number of generations in NSGA-II
pareto_sol	**178**	**Amount of pareto solutions**

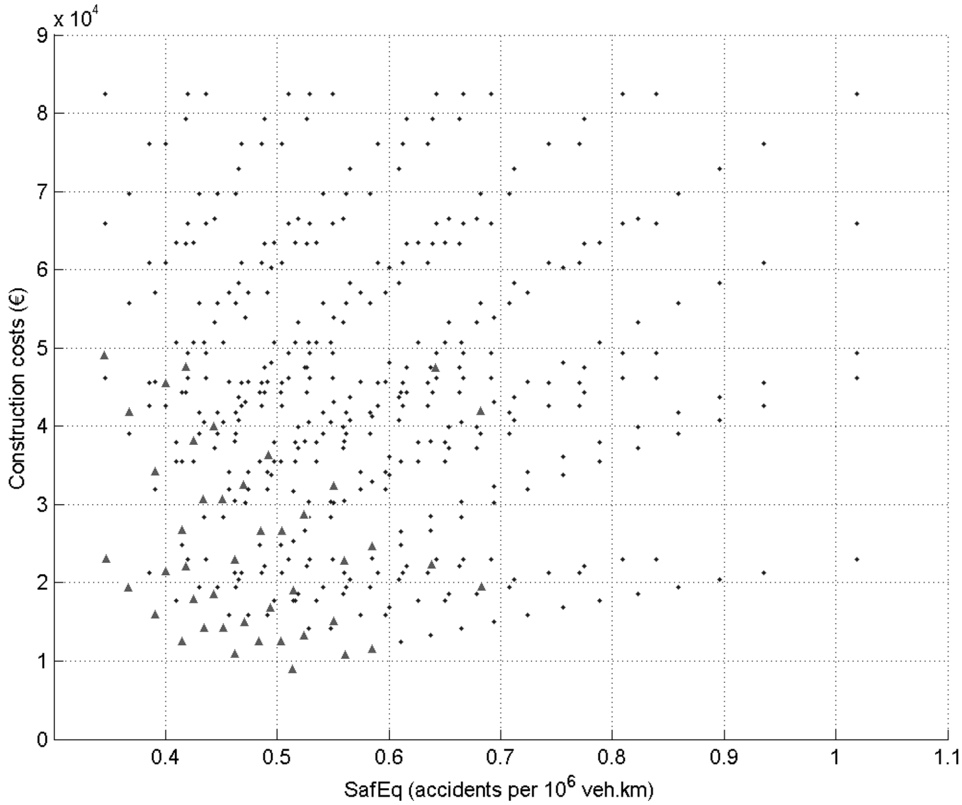

Figure 3. Two-axis projection view of the Pareto frontier of the problem

Figure 3 shows a projection view on the objectives "Limitation of the constructions costs" and "Road design and safety equipment" of the successive populations (dots) and the nondominated solutions of the final population (triangles). In this problem, all the objectives must be minimized. We clearly observe a convergence of the sets of initial and intermediate solutions towards an improved final population, even if the projection from eight to two dimensions implies a loss of information. At the end of the genetic process, we obtain nondominated solutions with better evaluations on the criteria of the problem.

These interesting results illustrate the utility of using a multi-objective evolutionary algorithm to describe the problem, given that it proceeds to an efficient and extensive design space exploration. Moreover, it allows us to consider several criteria at the same time and then to give a relevant information to the decision maker.

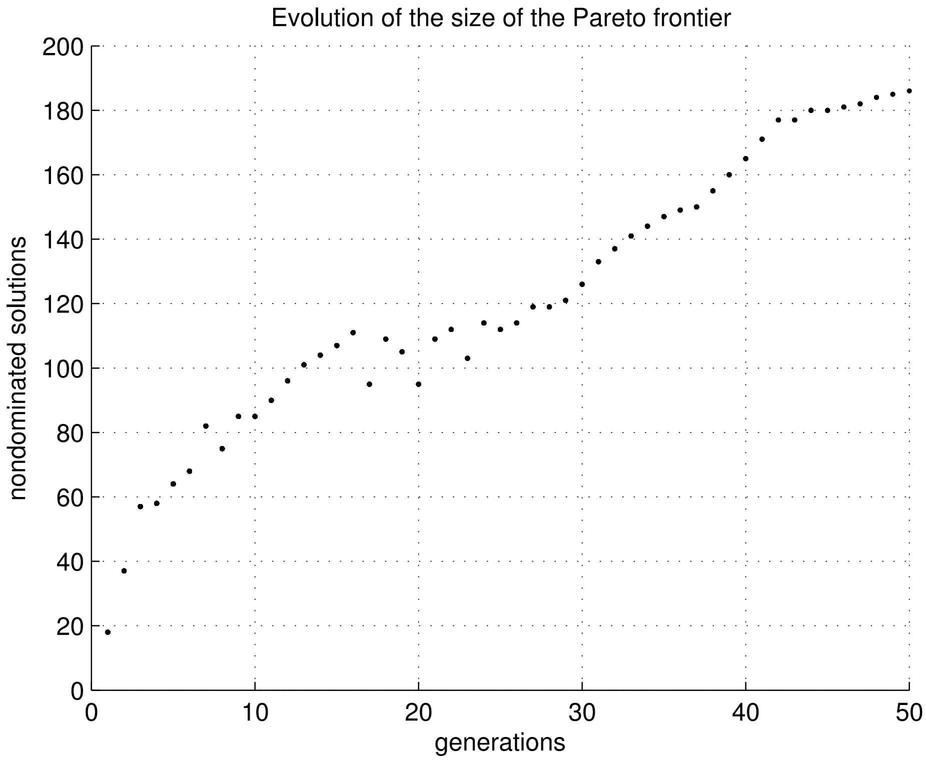

Figure 4. Evolution of the dimension of the Pareto front during the evolutionary algorithm

5. Performance evaluation and Pareto front structure

Once the genetic algorithm has been developed, we can take an interest in the study of performance indicators and the analysis of the properties of the design space. These indicators allow us to quantify the quality of the solution set and the global performance of the NSGA-II algorithm. In the following section, we use some classical indicators from the literature in order to evaluate the convergence of the model (contribution, binary -indicator), the diversity of the nondominated solution set (spread) or both convergence and diversity (binary hypervolume indicator) (Taalbi 2009).

5.1 *Convergence-based indicators*

According to the literature, the convergence-based indicators allow us to quantify the effectiveness of a set of nondominated solutions by evaluating their nearness to the optimal Pareto front.

5.1.1 Dimension and convexity of the Pareto front

The dimension of the Pareto front is a simple metric which evaluates the size of the Pareto frontier and its evolution during the genetic process. Figure 4 illustrates the evolution of the dimension of the Pareto frontier towards the final value of 186 nondominated solutions. Considering the simplified nature of the example, we have measured the exact Pareto front of the full population. For this example, it is composed of 552 unique nondominated solutions in the objective space (but 952 alternatives in the decision space). For a limited population of 50 alternatives and after 50 generations, the approximated

Pareto front is then composed of about 34% of all the nondominated solutions of the full multicriteria problem (and 44% after 100 generations, 56% after 150 generations). Consequently, due to the loss of information, it is crucial to analyse the convergence and the distribution of the approximated Pareto front in order to determine if it constitutes a good approximation of the exact Pareto front.

In addition, we have measured the convexity of the Pareto front by evaluating the position of the nondominated solutions relatively to a hyperplane. Considering a multicriteria problem with k criteria, this hyperplane is defined from k points randomly selected on the Pareto front. After 30 runs of the algorithm, we obtain an average value of convexity of 82.5%. It indicates that the Pareto front is globally convex, but some nondominated solutions can be missed due to local concavity.

Finally, solving the exact problem requires a calculation time of about 15 minutes while the solving of the limited problem (50 alternatives and 50 generations) requires a calculation time of 30 seconds. For this simplified example, it corresponds to only 3% of the calculation time of the full problem. Considering more complex problems, this significant win constitutes a very interesting . All the tests have been conducted on a computer with Intel Core i5 CPU 2.40 Ghz and 4,00GB of memory.

5.1.2 Contribution

The contribution is a convergence-based binary indicator (Taalbi 2009). During the genetic process, we measure the contribution of an approximation set PO_1 relatively to another approximation set PO_2 by calculating the ratio of nondominated solutions produced by PO_1 in the merged set of Pareto solutions $PO*$ (or $PO_1 \cup PO_2$). In the following equation, PO is the set of solutions in $PO_1 \cap PO_2$, W_1 the set of solutions in PO_1 that dominate some solutions of PO_2 and N_1 the set of non-comparable solutions of PO_1.

$$Cont\,(PO_1/PO_2) = \frac{\frac{\parallel PO \parallel}{2} + \parallel W_1 \parallel + \parallel N_1 \parallel}{\parallel PO^* \parallel} \tag{13}$$

At each generation, we generate a merged population ($PO*$) from the union of the new population (PO_1) and the previous population (PO_2). Then, we calculate the contribution of the new set relatively to the previous set at each step of the genetic process. Figure 4 illustrates the evolution of the contribution indicator.

The contribution metric of PO_1 relatively to PO_2 gives values between 1.0 and 0.3 for the first 20 iterations of the experiment, which means that the genetic algorithm quickly improves the set of nondominated solutions. Then, we observe a linear decrease of the contribution up to a value of 0.2 in the last iteration of the model, which indicates a convergence of the model.

5.2 *Diversity-based indicators*

A second type of performance indicators is the diversity-based indicators (Taalbi 2009). According to the literature, they measure the uniformity of distribution of the obtained solutions in terms of dispersion and extension. Within the framework of this research, we have studied the diversity of the nondominated solutions with the assistance of the spread indicator only (mainly because of the high computational cost involved by this type of indicators).

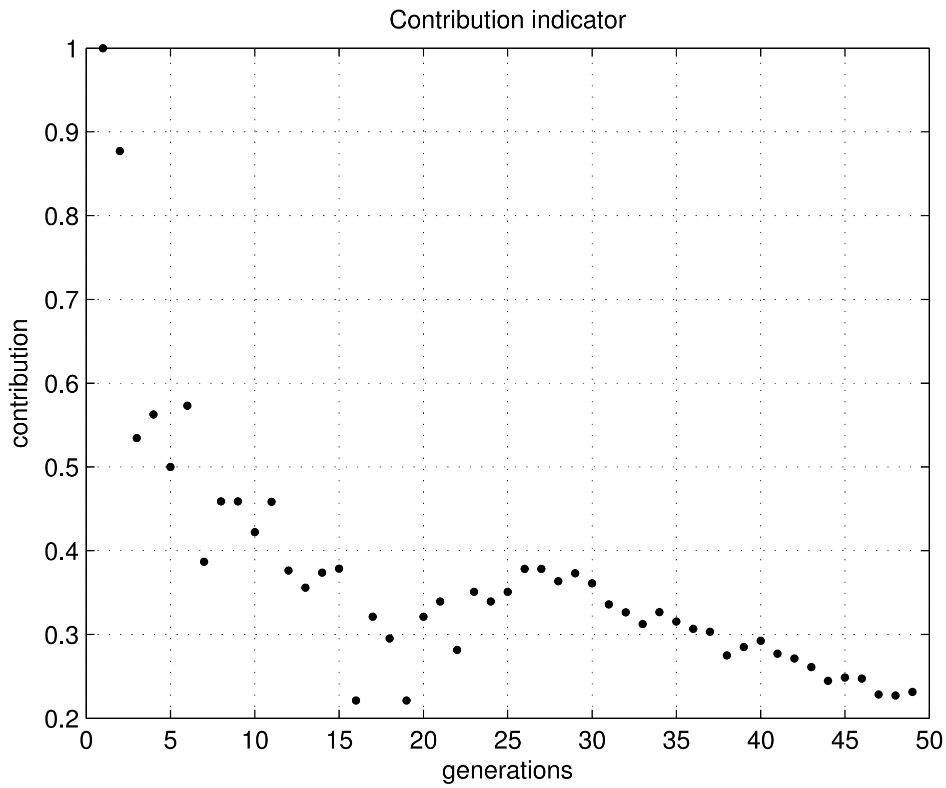

Figure 5. Evolution of the contribution indicator

5.2.1 Spread

The spread indicator is noted I_S. It measures the dispersion of the approximation set A over the Pareto front with a neighborhood parameter $\sigma > 0$ and a fitness function F(u) (Taalbi 2009).

$$I_S = \frac{\sum_{u \in A} | \{u' \in A : \| F(u) - F(u') \| > \sigma\} |}{|A| - 1} \tag{14}$$

The interpretation of the spread indicator is then quite simple: the closer is the measure to 1, the better is the spread of the approximated set A. Figure 6 illustrates the result of the spread indicator depending on the value of the neighborhood parameter σ. For values of σ below 1.2, the values of I_S range from 1.0 to 0.95 which corresponds to a very good spread of the nondominated solutions of the approximated set. For values of σ between 1.2 and 1.6, we observe a decrease of the values of I_S up to 0.8 which indicates that the solutions are still well spread over the Pareto front. Then, the values of I_S drop quickly from 0.8 up to 0 for values of σ between 1.6 and 2.1 and above. We can conclude from this figure that the Pareto-optimal front is globally well spread for values of below 1.5.

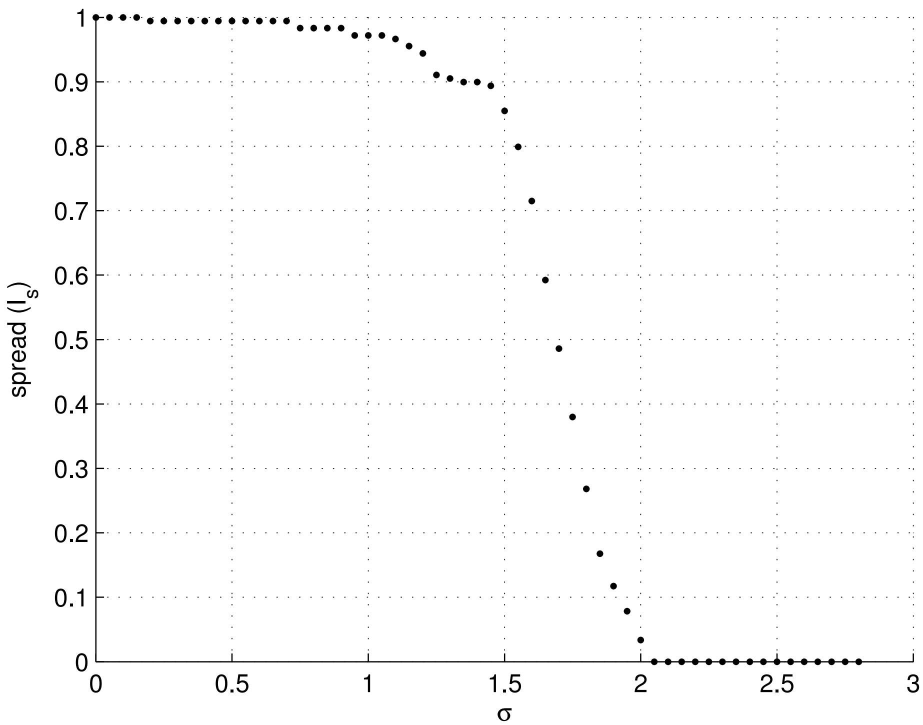

Figure 6. Evolution of the spread indicator with σ

5.3 *Hybrid indicators*

5.3.1 Hypervolume

The hybrid indicators both combine diversity and convergence measures. The hypervolume indicator can be declined into its unary and its binary form. Here, we have only considered the binary hypervolume indicator I_H. According to Zitzler et. al (1998, 2003), considering a reference point Z_{ref}, the binary hypervolume metric measures the volume of the objective space portion which is weakly dominated by the reference set Z_N and not by the approximation set A. The more the value of the hypervolume metric is close to 0, the more the approximation set A is close to Z_N.

In practical, this reference point can be set as the upper bound of each objective of the problem. For this example, the reference point Z_{ref} is the ideal point of the multicriteria problem where all the criteria are simultaneously optimised. Additionally, due to the simplified nature of the example, we have calculated the Pareto front of the exhaustive problem to generate the reference set Z_N.

Figure 7 shows the evolution of the volume of the objective space portion which is weakly dominated by Z_N but not by A. We clearly observe the convergence of the model after 30 generations. It indicates that the approximation set A is good and well distributed in comparison with the reference set Z_N.

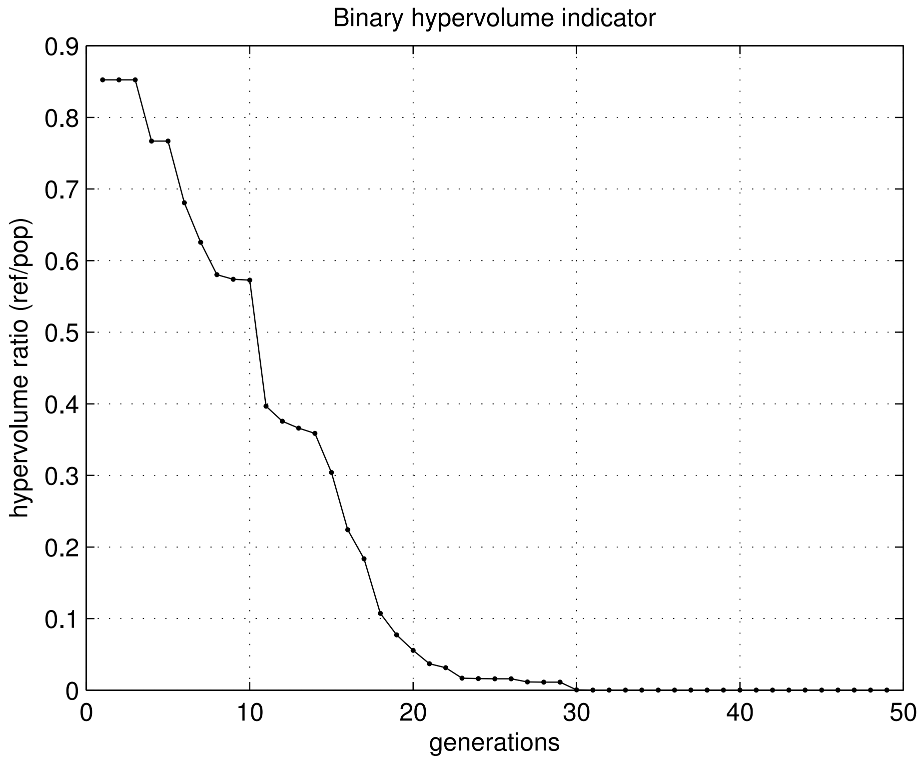

Figure 7. Binary hypervolume indicator during the genetic process

6. Conclusions and further developments

In this study, we have developed an innovative model to assess both the road safety and the sustainable performance 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. The performance indicators illustrate the quality of the solutions generated by the algorithm in terms of convergence and diversity. In particular, the results obtained from the computation of the binary hypervolume indicator show the quality of the approximation set given by our model. Moreover, the replicability of the results after several runs of the algorithm proves the robustness of the model.

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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References

Aarts, L., Wegman, F. 2006. *Advancing sustainable safety: National Road Safety Outlook for 2005-2010.* SWOV, Leidschendam.

Belgian Road Research Centre (BRRC). 2006. *Code de bonne pratique pour le choix du revêtement bitumineux lors de la conception ou de l'entretien des chaussées.* BRRC Press. BRRC R78/06.

Boutefeu E. 2008. *Prendre en compte le développement durable dans un projet : guide d'utilisation de la grille RST02.* Centre d'tudes sur les rseaux, les transports et l'urbanisme, Paris, France.

COST. 2008. "The way forward for pavement performance indicators across Europe." In *COST Action 354 Performance Indicators for Road Pavements*, COST Office and Austrian Transportation Research Association, July 2008.

Deb K. and Agarwal R. B. 1995. "Simulated Binary Crossover for Continuous Search Space." In: *Complex Systems*, 9:115-148, April 1995.

Deb, K., Pratap, A., Agarwal, S. and T. Meyarivan. 2002. "A Fast Elitist Multiobjective Genetic Algorithm: NSGA-II." In *IEEE Transactions on Evolutionary Computation 6 (2002)*, no. 2, pp. 182-197.

den Boer, L.C. and Schroten, A. 2007. *Traffic noise reduction in Europe : Health effects, social costs and technical and policy options to reduce road and rail traffic noise.* CE Delft, Nederlands.

European Commission. 2001. *European Transport Policy for 2010: Time to Decide - White Paper.* Communication from the Commission, COM (2001) 370 final, Brussels, Belgium.

European Commission. 2008. *Greening Transport: new Commission package to drive the market towards sustainability.* European Commission IP/08/1119, Brussels, Belgium.

European Commission. 2010. *Towards a European road safety area: policy orientations on road safety 2011-2020.* Communication from the Commission, COM (2010) 389 final, 2010, Brussels, Belgium.

European Environment Agency. 2011. *Energy efficiency and energy consumption in the transport sector.* Technical report ENER 023.

Federal Highway Administration (FHWA). 1992. *Safety Effectiveness of Highway Design Features, Volume III : Cross sections.* Federal Highway Administration Press, Washington DC.

Federal Highway Administration (FHWA). 2006. *Pedestrian and Bicyclist Intersection Safety Indices.* Federal Highway Administration Press, FHWA-HRT-06-125.

Gitelman V. and Hakker A.S. 2006. *Road Safety Performance Indicators: Manual.* European Commission, Deliverable D3.8 of the EU FP6 project SafetyNet, Brussels, Belgium.

Greenroads Foundation, 2013. *Greenroads Rating System v1.5.* Manual Guide.

Institut Belge pour la Sécurité Routière. 2012. *Go For Zero - Notre objectif tous : zéro tué.* IBSR Press release, Brussels, Belgium.

Institut Belge pour la Sécurité Routière. 2013. *Baromètre de la sécurité routière : Année 2013.* IBSR Press release, Brussels, Belgium.

Noël N., Leclerc C., Lee-Gosselin M. 2003. "CRC Index: Compatibility of Roads for Cyclists in Rural and Urban Fringe Areas" In *TRB 2003 Annual Meeting*, 2003.

Nossent P. 2011. "La certification Route Durable : une certification qui donne confiance." In *Colloque Route Durable*, Conseil Gnral du Nord, 31 May 2011.

Organization for Economic Co-operation and Development. 1999. *Safety strategies for rural roads.* OECD Publishing, Paris, France.

Office Fédéral de l'Environnement, des Fôrets et du Paysage (OFEFP). 1995. *Bruit de trafic routier : correction applicable au modèle de calcul du trafic routier.* Collection l'Environnement Pratique. Suisse.

Rouffaert A. et al. 2009. *Vademecum Veilige Wegen en Kruispunten.* Agentschap Wegen en Verkeer, Vlaamse Overheid.

Sarrazin, R. and De Smet, Y. 2011. "A preliminary study about the application of multicriteria decision aid to the evaluation of the road projects' performance on sustainable safety." In *Proceedings of 2011 IEEE International Conference on Industrial Engineering and Engineering Management*, Singapore, 6-9 December 2011.

Sarrazin, R., De Smet, Y. and Debauche, W. 2014. *Using multicriteria decision analysis to assess the sustainable safety performance of road projects at the design stage.* Technical Report SMG. Brussels, Belgium.

Service dEtudes Techniques des Routes et Autoroutes. 2008. *Accessibilité des territoires et des services : Notions et représentations.* Technical report.

Talbi E.G. 2009. *Metaheuristics : from design to implementation.* John Wiley & Sons.

Technical Committe 13 Road Safety, 2004. *Road Safety Manual.* PIARC World Road Association, Route 2 Market Limited.

Tingvall, C., Haworth, N. 1999. "Vision Zero: an ethical approach to safety and mobility." In *The 6th Institute of Transport Engineers International Conference of Road Safety and Traffic Enforcement: Beyond 2000.* Melbourne, 1999.

Walloon Region, 2009. *Projet de déclaration de politique régionale wallonne 2009-2014 : une énergie partagée pour une société durable, humaine et solidaire.* Walloon Region Press, Namur, Belgium.

Zegeer C., Steward R., Council F., Neuman T. 1994. "Accident Relationships of Roadway Width on Low-Volume Roads." In *TRB Record 1445*, Transportation Research Board.

Zitzler E., Thiele L. 1998. "Multiobjective optimization using evolutionary algorithms: A comparative case study." In *PPSN V Parallel Problem Solving from Nature*, Amsterdam, The Nederlands, 1998, pp. 292-301.

Zitzler, E., Laumanns, M., Fonseca, C. M., Thiele L. and Grunert da Fonseca, V. 2003. *Performance assessment of multiobjective optimizers: An analysis and review.* IEEE Transactions on Evolutionary Computation, 7(2):117132.