



TRANSPORT

ISSN 1648-4142 / eISSN 1648-3480

2016 Volume 31(3): 312–321

doi:10.3846/16484142.2016.1157830

AN ANALYTIC HIERARCHY PROCESS MODEL TO EVALUATE ROAD SECTION DESIGN

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first published online 30 March 2016

Abstract. The traffic system is as essential to modern society as the circulatory system to the human body. Road section design is therefore a key infrastructure activity for economic development, and multi-criteria decision-making can provide an interdisciplinary approach that moves beyond purely economic optimisation to include technological, technical and ecological factors. The present work describes applying the multi-criteria Analytical Hierarchy Process (AHP) method to evaluate road section design in an urban environment through differential weighting of various criteria and sub-criteria. The model is tested on a stretch of National Road D8 in the municipality of Podstrana near the city of Split (Croatia), which serves as an important route for commuters and tourists. The proposed AHP model provided reliable results that were robust to sensitivity analysis. This approach involving differential criterion weighting may prove useful for evaluating and selecting appropriate road section designs for this and other contexts.

Keywords: multi-criteria decision-making; analytic hierarchy process; road section design; intersection; roundabouts; sensitivity analysis.

Introduction

An efficient transport system is key to the economic and non-economic health of any country. Transport budgets are limited, so decision makers must select a subset of transportation projects for implementation. This involves trying to satisfy conflicting objectives measured in incommensurate units, the relative value of which involves political and moral dimensions, such as the value of a passenger hour or of human life (Avineri *et al.* 2000).

Multi-Criteria Decision-Making (MCDM) is well suited for dealing with the complexity of transportation project selection. It can help support the continuous planning and re-assessment necessary for optimising the use of available resources (Bendeković 2008) and deciding whether investment projects are reasonable and cost-effective. It can also take into account the social dimension of investment costs and benefits, which is critical for transportation projects of all sizes that have both social and economic impacts.

Numerous multi-criteria models have been applied to socially important investment projects, especially traffic infrastructure projects (Nowak 2005; Su *et al.* 2006; Barić *et al.* 2007; Aghdaie *et al.* 2012). These

methods differ primarily in their optimisation criteria, which always involve a combination of technological, technical, ecological and other criteria. One of the most frequently used multi-criteria models is the Analytical Hierarchy Process (AHP) model (Podvezko 2009). The AHP model has proven valuable not just in traffic sciences (Saaty 1995) but also in most other spheres of human activity, including civil engineering (Cerić, Marić 2011; Cerić *et al.* 2013; Karleuša *et al.* 2014), marketing (Gholami, Seyyed-Esfahani 2012), entertainment (Vidal *et al.* 2011) and selection of academic staff (Rouyendegh, Erkan 2012).

Road section design is an essential part of traffic infrastructure projects in which sections of the same road may need to be designed with different characteristics to meet local needs or accommodate local constraints. Despite the key role of road section design in determining the success and final costs of transportation projects, few studies have attempted to use AHP to carry out and assess such designs. Therefore, we describe here a case study applying the AHP method to the reconstruction of a stretch of road in the municipality of Podstrana, a suburb outside the major city of Split (Croatia).

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The main purposes of this study were to:

- study, describe and analyse current applications of the AHP method in transport-related problems, with emphasis on road section design;
- assess the feasibility of applying the AHP method to optimise parameters for reconstructing a stretch of road and associated intersections;
- propose a specific AHP model for such reconstruction with the corresponding weighting factors for criteria and sub-criteria;
- apply and verify the proposed AHP model.

This study involved a thorough review of the relevant literature as well as the creation of a database intended to support future development and application of AHP procedures and methods.

The first section summarises previous studies of the AHP method and its application for solving transport-related problems. The second section describes the MCDM process and main characteristics of the AHP method. The third section describes the development and application of AHP structures for evaluating two alternative road section designs to reduce traffic congestion on a stretch of road in Croatia receiving significant commuter and tourist traffic. The last section discusses the results and draws final conclusions.

1. Review of Previous Research

The AHP method is increasingly important for solving transport-related problems (Abastante *et al.* 2012; Barić, Starčević 2015). While single-criterion and traditional cost-benefit analyses are still used in transport decisions, MCDM methods are increasingly replacing them (Barić *et al.* 2007). One well-studied method is the AHP method.

This method has been used most often in railway transport for planning railway routes (Barić *et al.* 2007) and optimising passenger transport (Sivilevičius, Maskeliūnaitė 2010). In air transport, it has been used most often for choosing the optimal means of transport (Yedla, Shrestha 2003) and optimising airport expansion (Vreeker *et al.* 2002). In logistics, the method has been applied most often to process optimisation (Poletan Jugović *et al.* 2007; Erkan, Can 2014) and selection of the optimal supply company at the national and international levels (Hashemkhani Zolfani *et al.* 2012). A small part of the literature has applied the AHP method to postal transport (Bošnjak *et al.* 2005) and maritime transport (Đelović, Medenica Mitrović 2010).

In road transport, the AHP method has been applied most often to decisions related to planning and investing in transport infrastructure (Holguín-Veras 1995; Klungboonkrong, Taylor 1999; López, Monzón 2010; Bottero *et al.* 2012; Wang *et al.* 2013), especially pavement maintenance (Tabucanon, Lee 1995; Wu *et al.* 2008; Farhan, Fwa 2009; Moazami *et al.* 2011; Sun, Gu 2011) and assessment of the safety of roads (Haghighat 2011; Wiethoff *et al.* 2012) and intersections (Basile *et al.* 2010). In urban settings, the AHP method has served most often to optimise transport planning in

cities (Yu *et al.* 2011), selection of public garage locations (Deluka-Tibljaš *et al.* 2011), and public passenger transport (Jakimavičius, Burinskienė 2009; Chung *et al.* 2009). For evaluating sustainable urban mobility of cities, Campos proposed a procedure based on an index calculated through a weighted combination of multiple criteria (Campos 2009).

For the present study, the authors surveyed the literature for applications of the AHP method for resolving transport-related problems (Fig. 1). The following literature sources were searched for relevant studies:

- the scientific journals *International Journal of the Analytic Hierarchy Process*, *Promet – Traffic&Transportation* and *Transport*;
- studies published through the International Symposium on the Analytic Hierarchy Process (ISAHP) conferences;
- doctoral dissertations and undergraduate theses performed at the Faculty of Transport and Traffic Sciences of the University of Zagreb (Croatia).

The *International Journal of the Analytic Hierarchy Process* was selected because of its primary purpose of publishing articles about MCDM based on AHP and the Analytical Network Process (ANP). The journal *Promet – Traffic&Transportation* was selected because it is the leading transport journal in the country where the present study was carried out. The journal *Transport* was selected because it is internationally renowned for publishing high-quality traffic research. This literature survey showed that 13% of articles published over the past 5 years in *International Journal of the Analytic Hierarchy Process* applied the AHP method; the corresponding percentage in *Promet – Traffic&Transportation* is 1% and in *Transport* – 3%. The frequency with which the AHP method has been applied to various transport fields, based on analysis of studies published at ISAHP conferences, is shown in Fig. 1. The method has been applied most often to road transport problems (27%), followed by rail transport (18%) and air transport (14%).

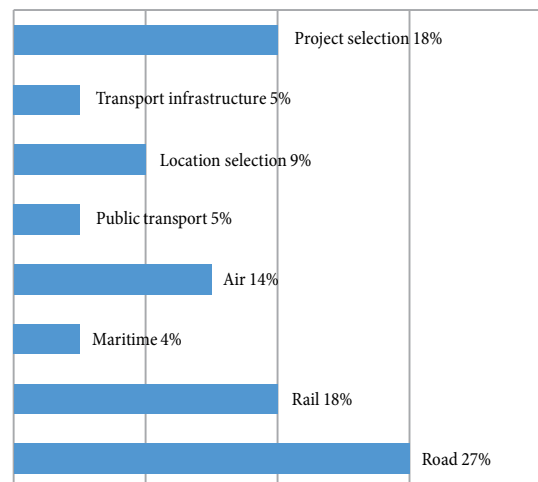


Fig. 1. Frequency with which the AHP method has been applied to different types of transport projects in the literature

The method has also been applied often to prioritising transport projects (18%) and selecting the locations of transport terminals (9%). Less often, the method has been applied to selecting the optimal public transport system (5%) or sustainable transport infrastructure (5%), as well as to problems of maritime transport (4%). Survey of undergraduate theses indicates that the AHP method has most often been applied to road transport, particularly for selecting the optimal design for reconstructing intersections.

Like other multi-criteria models, the AHP method is often implemented in conjunction with other methods, most frequently ANP, SWOT analysis, cost-benefit analysis and Fuzzy-AHP (FAHP). SWOT analysis allows strategic planning based on non-quantitative assessment of strengths, weaknesses, opportunities, and threats to the project. It is most often used for situational analysis as part of an organisation's marketing strategy. Recently the combination of AHP and SWOT has been used to analyse the implementation of Near-Field Communication (NFC) technology at Telecom Italia (Mehmood *et al.* 2014). In that work, the authors assessed negative and positive external and internal factors related to NFC adoption by the telecommunications industry. The resulting analysis is intended to help decision makers develop strategies for large-scale deployment.

Lately, the AHP method has been applied in conjunction with fuzzy-logic, termed FAHP. For example, Arslan (2009) presented a decision support model involving public involvement and oversight to help policy makers select transportation projects for implementation. The authors presented a set of 'if-then' rules based on Weber's psychophysical law of 1834 to translate fuzzy numbers into subjective preferences for pairs of alternatives. The AHP method was used to assign preferences to the alternatives. To demonstrate their procedure, the authors described how the method can be used to choose between a public bus route proposed by municipal authorities and another route proposed by private agencies.

Fouladgar *et al.* (2012) offered a new fuzzy multi-criteria decision-making method, based on COmplex PROportional ASsessment (COPRAS) and AHP, for evaluating asset maintenance strategies. FAHP was used to calculate the weights of evaluation criteria, and then alternatives were ranked based on fuzzy set theory and COPRAS. More recent studies have demonstrated various possible applications of FAHP and have compared it with the conventional AHP method (Erkan, Can 2014; Rossi *et al.* 2013). Studies have also validated a new method, called the Fuzzy-Based Evaluation Method (F-BEM), and shown its usefulness for evaluating the sustainability of alternative transport policies, such as to reduce pollution (Rossi *et al.* 2013).

Lin *et al.* (2008) have proposed an adaptive AHP approach (A³) based on a soft computing scheme, namely Genetic Algorithms. The A³ approach is used to recover the real number weightings of the various AHP criteria and to generate a function for improving the Consistency Ratio (CR) of pairwise comparisons. Those

authors validated the A³ approach by showing how it could be used to determine the weightings of the multiple criteria for a best-value bid in construction management. Those authors found the A³ method to lead to a cost-effective, faster and higher-quality decision than the traditional AHP method.

Our review of the literature indicates that the AHP method has been applied to all types of transport problems, but that few studies have applied it to the optimal choice of road section and/or intersection design. This gap in the literature was in large part the inspiration for the present work.

2. Methodology

MCDM involves optimising one or several objective functions, where the objective is defined as the condition of the system to be decided, over a defined set of possible solutions, corresponding to the various alternatives available to the system. The alternatives can differ in one of several attributes (criteria). Multi-criteria problems, in contrast to single-criterion problems, involve several objective functions and criterion functions.

Thomas Saaty developed the AHP method to guide complex decisions involving a large number of decision makers and criteria (Saaty 1995, 2008). It is one of the best-characterised and validated methods for MCDM. It can perform better than other multi-criteria methods because it can easily be adapted to different numbers of attributes (criteria) and alternatives, which can be described both quantitatively and qualitatively. Multi-criteria analysis takes the following mathematical form:

$$\max \{f_1(x), f_2(x), \dots, f_n(x), n \geq 2\} \quad (1)$$

with the constraints:

$$x \in A = [a_1, a_2, \dots, a_m], \quad (2)$$

where: n – number of criteria, $j = 1, 2, \dots, n$; m – number of alternatives, $i = 1, 2, \dots, m$; f_j – criteria, $j = 1, 2, \dots, n$; a_i – alternative for consideration, $i = 1, 2, \dots, m$; A – set of all alternatives.

According to Saaty (2008), making a decision about priorities means decomposing the decision process into the following steps:

Define the problem and determine the kind of knowledge sought.

Structure the decision hierarchy from top to bottom as follows: the goal of the decision, followed by the objectives from a broad perspective, then criteria on which subsequent elements depend, and finally the set of alternatives.

Construct a set of pairwise comparison matrices. Each element in an upper level is compared with the elements in the level immediately below.

Use the priorities from the comparisons to weight the priorities in the level immediately below, and repeat this for every element. Then add together the weighted values for each element in the level below in order to obtain its overall or global priority.

This process of weighting and adding should continue until the final priorities of the alternatives in the bottom level are obtained. In order to define the relative importance of criteria and sub-criteria with respect to the objective of research, criteria are ranked using a Saaty scale (Saaty 2008), which features five main levels of intensity (1 – equal importance, 3 – moderate importance, 5 – strong importance, 7 – very strong or demonstrated importance, 9 – extreme importance), as well as four intermediate levels (2 – weak or slight, 4 – moderate plus, 6 – strong plus, 8 – very, very strong).

The best alternative is selected based on the defined total weight priority vector by synthesising all weight vectors, and it is described by the following expression:

$$W_i = \sum_{j=1}^n c_j w_{ij}, \quad \forall i = 1, \dots, m, \quad (3)$$

where: W_i – weight, priority of alternative i ; c_j – weight of criterion j ($j = 1, 2, \dots, n$); w_{ij} – weight of alternative i regarding criterion j ; m – number of alternatives; n – number of criteria.

Saaty proved that for the consistent reciprocal matrix, the largest eigenvalue is equal to the number of comparisons, or $\lambda_{\max} = n$. Then he defined a measure of consistency, called the Consistency Index (CI), which indicates the deviation or degree of consistency using the following formula:

$$CI = \frac{\lambda_{\max} - n}{n - 1}. \quad (4)$$

Saaty proposed that the CI should be compared with the corresponding random CI (RI). Saaty randomly generated reciprocal matrices using scale and calculated the RI to determine whether it was approximately 10% or less.

The CR compares the CI with RI:

$$CR = \frac{CI}{RI}. \quad (5)$$

If CR is smaller or equal to 10%, the inconsistency is acceptable. If CR is greater than 10%, the preference needs to be revised.

3. Using the AHP to Evaluate Road Section Design

3.1. Definition of the Problem

Many parameters must be taken into consideration when planning the reconstruction of road sections and corresponding intersections within a spatially restricted urban environment. This is particularly important when selecting the optimal alternative among various possibilities based on the most important parameters. The relative importance of the various parameters in this decision-making strongly depends on the type of problem and the perspective of the stakeholder. The relative weight of each factor can be defined through expert opinion based on surveys or panel discussions (Basile *et al.* 2010). Another possibility is to use the AHP method to weight the various factors, as one of us has pointed out (Strujić 2014). Here we apply this method to a particular case study.

The stretch of national road D8 from Poljička road to Put Starog sela road, 0.5 km long, lies in the municipality of Podstrana (population: 9129), a suburb to the southeast of the major city of Split (population: 178102). This stretch of road contains four level intersections (Fig. 2).



Fig. 2. Image of the stretch of national road D8 under investigation

The road stretch links the city of Split, which is the largest tourist destination in Dalmatia, with the smaller tourist city of Omiš to the east, the large tourist area on the Makarska Riviera and ultimately the tourist city of Dubrovnik. On the section of road extending from the direction of Split to the intersection of national road D8 and Poljička road, traffic runs in four lanes (two in each direction), and then in two lanes (one in each direction) after the intersection. Two partially signalised intersections (blinking yellow), labelled as intersection 1 (D8 – Poljička road) and intersection 2 (D8 – Street Gospe od Siti-Jurasova road), lie 100 m apart. Two unsignalised intersections, labeled intersection 3 (D8 – Domovinskog rata street) and 4 (D8 – Put Starog sela road) lie 300 m away from intersections 1 and 2.

Analysis of traffic flows along this stretch of road during morning and afternoon peak hours, when commuters are traveling between the suburb and Split, has shown significant traffic jams (Strujić 2014). This is particularly true on weekends during the summer tourist season. From intersection 1 the traffic pile-up can extend for 2–3 km, even up to 10 km, causing delays of a few hours. In 2013, the traffic counter installed near intersection 1 recorded the highest average annual daily traffic (49443 vehicles) and the highest average summer daily traffic (57642 vehicles) of all counters installed in Croatia (Strujić 2014).

3.2. The AHP Model

A theoretical framework for road section design (reconstruction) was defined including all relevant road design parameters extracted from the research literature and university textbooks on road and civil engineering design. These parameters constituted five criteria and associated sub-criteria (Fig. 3) that were used to evaluate two alternative reconstructions of the D8 stretch indicated in Fig. 2. Our choice of criteria and sub-criteria was also based on insights into modeling and optimising intersections (Legac 2008) and other studies (Barić et al. 2007; Pilko 2014; Barišić 2014). The perspective adopted in our AHP model was that of the road traffic engineer.

Although Legac (2008) highlights the significance of all criteria and sub-criteria as well as their correlations, the present authors have shown that they can be divided structurally and conceptually (Barić et al. 2007; Pilko 2014; Barišić 2014). Transport–Technical–Technological (TTT) criteria were derived from fundamental transport–construction criteria reflecting micro and macro aspects of modeling intersections. Some TTT sub-criteria were based on previous studies, i.e. design speed (Šurdonja et al. 2013; Pilko et al. 2014) and spatio-urban impact (Basile et al. 2010; Barišić 2014). The remaining four criteria and their associated sub-criteria reflected primarily studies by one of us (Pilko 2014) and analysis of functional efficiency and costs (Mauro, Cattani 2012). The sub-criterion of number of conflict points was selected based on research by one of us (Strujić 2014).

We collected and analysed data from a survey of 61 road traffic engineers (Pilko 2014) in order to generate weighting functions for objectives, criteria and alternatives based on the Saaty scale. Criteria weighting is reported in that study in detail. The results of that survey represent the consensus assessment of all the experts

surveyed, and this assessment was used to develop the AHP model. After criteria were selected, analysed and ranked, data were entered and processed in the software *Expert Choice 11.5*.

The highest weighting coefficient (0.286) was associated with the criterion *Functional efficiency* (EF), while the lowest coefficient (0.115) was associated with the criterion *Ecological* (ECO). The low inconsistency among observed criteria (0.03) suggested a well-structured model as shown in Table.

Table. Criteria priorities

Criteria	Criteria weights (priorities)
Functional efficiency	0.286
Traffic–Technical–Technological	0.245
Safety	0.211
Cost	0.143
Ecological	0.115
Inconsistency = 0.03	

3.3. Results of the AHP Method

Assessment of sub-criteria and proposed alternatives was also carried out using *Expert Choice 11.5*. The two alternatives were as follows (Strujić 2014). The first alternative, called Variant 1 (V1), involved introducing and coordinating signaling at intersections 1 (D8 – Poljička road) and 2 (D8 – Street Gospe od Siti-Jurasova road), as well as adding a traffic lane for turning left from main road D8 at intersections 3 (D8 – Domovinskog rata Street) and 4 (D8 – Put starog sela road). The second alternative, called Variant 2 (V2), involved converting intersection 1 into a roundabout and closing intersec-

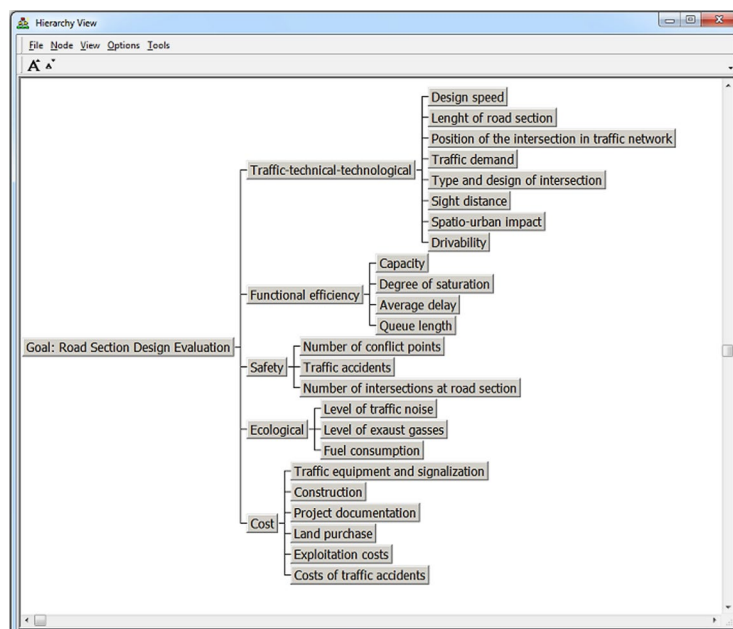


Fig. 3. Hierarchy structure of the AHP model

tion 2. In this alternative, intersection 1 would feature on its south-eastern side three new approaches from Gospe od Siti street, D8 – Omiš and Jurasova street. Intersection 3 would also be closed, and Domovinskog rata street would be connected via by-pass with Put Staroga sela street. Finally, an extra lane for left turns would be added to intersection 4.

In the determination of the importance of TTT criteria, the highest weighting coefficient (0.182) was assigned to the sub-criterion *Length of road section*, and the smallest weighting coefficient (0.055) to the sub-criterion *Spatio-urban impact*. Overall CR of the model was 6%, which is below the cut-off of 10% (section 2), indicating a well-structured model.

In determining functional efficiency, the sub-criterion *Capacity* received the highest weighting coefficient (0.486) and the sub-criterion *Queue length* the lowest (0.095). Overall CR of the model was 0.299%, again indicating a well-structured model. During assessment of traffic safety, all three sub-criteria were found to be correlated and therefore were ranked as equally important. For this reason, total inconsistency of the model was 0%.

In the determination of ecological impact, the sub-criterion *Level of exhaust gases* was assigned the highest weighting coefficient (0.500), and the sub-criterion *Level of traffic noise* the lowest (0.167). Overall model CR was 0%.

In the determination of costs, the sub-criterion *Construction cost* received the highest weighting coefficient (0.296) and the sub-criterion *Traffic equipment and signalisation cost* the lowest (0.056). Overall model CR was 0.504%. The results of the AHP modelling, together with weighting of all criteria and sub-criteria, are shown in Fig. 4.

3.4. Sensitivity Analysis

It can be difficult to assess the efficiency of a transport infrastructure investment because cost-benefit analyses conducted before the project may not accurately reflect what will happen over the 10- to 30-year lifespan of the investment. Hence, it can be useful to perform sensitivity analysis, which assesses investment efficiency as a function of input values for individual parameters. In this way, the stakeholder can determine whether the project is acceptable even if certain critical parameters deviate from their expected values. Critical parameters are those that can significantly affect the overall efficiency of the project and can change over the project's lifespan.

Sensitivity analysis is reasonably straightforward within the AHP method. Changing priorities of the elements on higher levels influences the final results more than changing the priorities of lower level elements. Therefore, we altered the weights of various criteria and tested how the changes affected the recommended alternative for road section reconstruction.

Only the criterion *Cost* gave higher priority to Variant 1 (Fig. 5). Systematically changing the weighting for *Cost* showed that Variant 1 gained the advantage over Variant 2 only when the weighting was increased from 0.143 to at least 0.584 (Fig. 6).

Discussion and Conclusions

Using the AHP method to assess a large number of alternatives on the basis of comprehensive parameters can significantly improve the quality of decision-making about investments in transport infrastructure. Here we report one case study suggesting that the AHP method can work well for choosing the optimal design (recon-

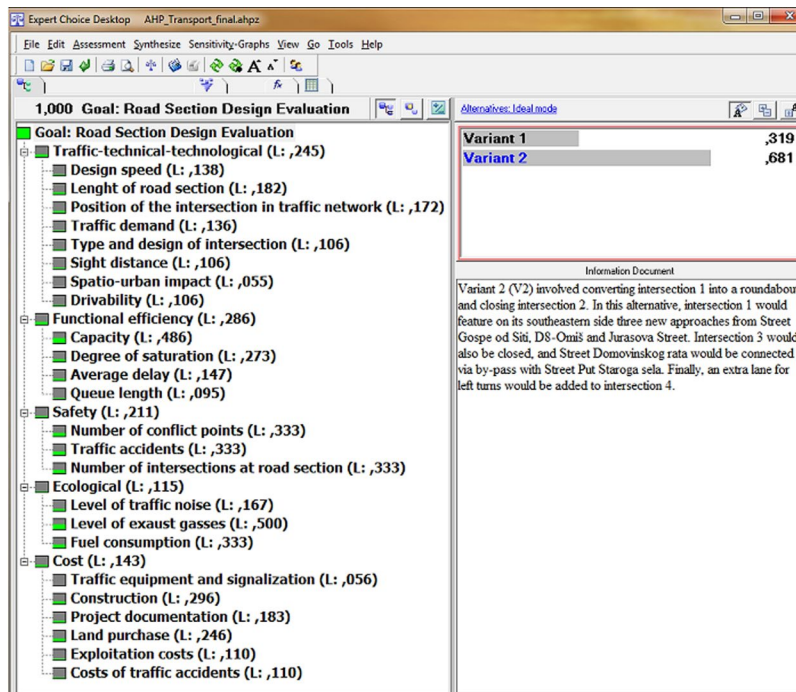


Fig. 4. Weighting factors for criteria and sub-criteria in the AHP model

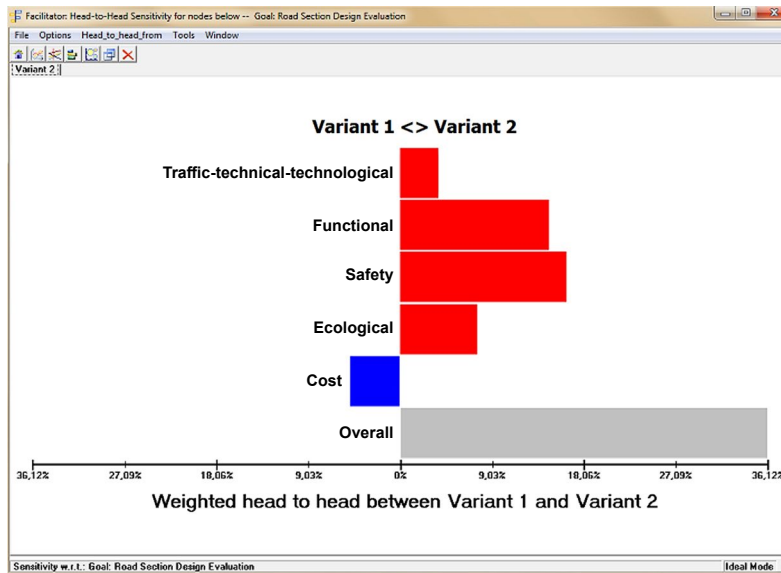


Fig. 5. Priority of alternatives for different criteria depicted using a head-to-head graph

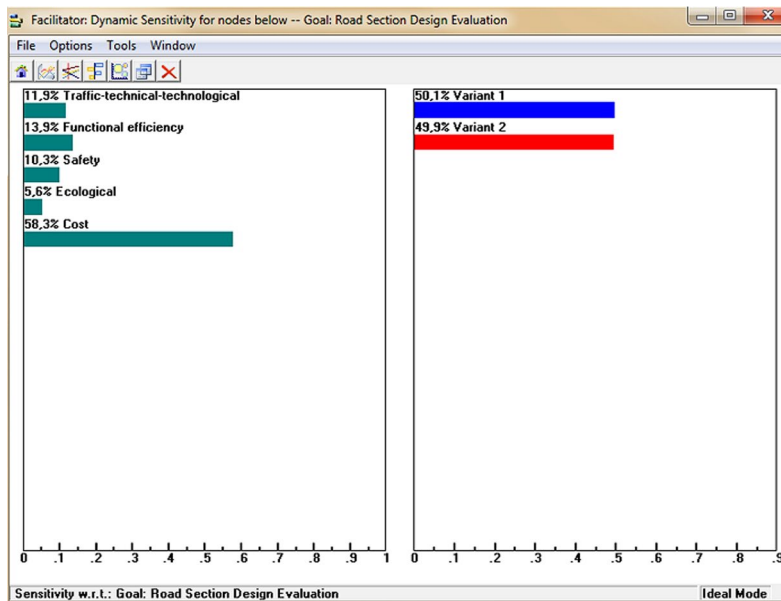


Fig. 6. Sensitivity of the recommended alternative to changes in the weighting of the criterion *Cost*, depicted using a dynamic graph

struction) of a road section in an urban area. This is the first such use of the AHP method, extending previous studies showing that the AHP method also works well in several other types of transport-related problems.

Of the 5 criteria selected for the AHP model, the most important was *Functional efficiency*, and the least important was *Ecological*. Inconsistency among the observed criteria was 0.03, indicating that the model was well structured. Inconsistency was similarly low for AHP structures of sub-criteria, among which *Length of road section*, *Capacity*, *Level of exhaust gases* and *Construction cost* were most important, while *Spatio-urban impact*, *Queue length*, *Level of traffic noise* and *Traffic equipment and signalisation costs* were least important.

Variant 2 proved to be an optimal design solution, and sensitivity analysis showed this result to be robust, affected only by a large increase in the weighting of the criterion *Cost*.

Since this study is the first to our knowledge to apply the AHP method to road section design, it is difficult to compare our results with others in the literature. Therefore, further work is needed to confirm the validity of our approach. One thing to note is that the study area sees significant traffic during business commuting hours as well as during the summer due to large tourism flows. Future studies should examine whether our approach works in urban areas with other traffic dynamics. We expect our choice of parameters can capture a reasonable range of situations, since we selected them

from the literature and a field survey of 61 road design experts in Croatia. Our parameters combined the factors most frequently used to evaluate projects, such as cost, safety, and ecological and social impact (Sivilevičius, Maskeliūnaitė 2010; Teng *et al.* 2010; López, Monzón 2010; Deluka-Tibljšaš *et al.* 2011; Abastante *et al.* 2012) together with traffic-focused parameters, i.e. TTT and functional efficiency criteria. While these traffic-focused parameters may limit the generalisability of our AHP model, it may be possible to supplement them with construction-related ones, such as configuration of the terrain, available surface, and horizontal and vertical elements (Legac 2008; Monajjem *et al.* 2013).

This study featured several limitations. One was that our data on the number and movements of traffic flow in the study area turned out to be inadequate for assessing functional efficiency or level of service, preventing us from simulating micro and macro aspects of traffic movements and flow using such tools as *PTV Visum*. Future studies should address these issues.

Future work should also conduct a survey of road traffic engineering experts from outside Croatia and consider perspectives of other stakeholders, such as civil engineer, economist, ecologist, or urban planner. This input may significantly alter the choice and weighting of criteria and sub-criteria, which may affect the recommended road section design.

It is also possible that combining our AHP method with other MCDM models may improve its performance, versatility or robustness. Models that may complement AHP include ANP (Cerić *et al.* 2013), SWOT (Mehmood *et al.* 2014), FAHP (Avineri *et al.* 2000; Arslan 2009; Karleuša *et al.* 2014) and COPRAS-G (Aghdaie *et al.* 2012).

The proposed AHP model with its criteria weighting structure may help policy makers select appropriate road section design projects for implementation. The model and the associated database may prove a useful and adaptable tool for dealing with a variety of problems.

Acknowledgements

The research described in this paper was conducted within the scope of the research project 'Correlation between Design and Safety at Roundabouts' (No. 135-000000-3313), funded by the Ministry of Science, Education and Sports of the Republic of Croatia.

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