Application of multi-criteria assessment for the selection of at-grade intersections

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Abstract

The paper deals with the problems of multi-criterion assessment of level intersections in urban and rural areas. In first part of this paper will be described developing methodology, including used multicriteria decision analysis method, chosen criterions and selected weights for each criterion. The prepared methodology will be applicable not only for designers, but within preliminary assessment also for the investor and for the state administration bodies.

The application of this methodology on chosen intersection types will be described in second part of the paper. Chosen intersection types are modelled in Aimsun micro-simulation software to define necessary input data usable in methodology. The achieved results will serve for the determination of a suitable multi-criterion assessment methodology, and also for the relevant model gauging, i.e. evaluation of individual criteria and the determination of their respective weights.

Keywords: multi-criteria assessment; at-grade intersection; safety; costs; noise pollution; ecological influence; micro simulation modelling

Résumé

L’article traite des problèmes d’évaluation multicritère des croisements à niveau dans les zones urbaines et rurales. Dans la première partie de cet article sera décrit la méthodologie de développement, y compris l’utilisation de la méthode multicritère d’aide à la décision, les critères choisis et poids sélectionnés pour chaque critère. La méthodologie préparée sera applicable non seulement pour les concepteurs, mais dans l’évaluation préliminaire également pour l’investisseur et pour les organes de l’administration de l’Etat. L’application de cette méthodologie sur des types d’intersections et des carrefours choisis sera décrite en deuxième partie de ce document. Les types d’intersections choisies sont modélisés dans le logiciel de micro-simulation AIMSUN pour définir les données d’entrée nécessaires utilisables dans la méthode. Les résultats obtenus serviront pour la détermination d’une méthodologie d’évaluation multicritère approprié, et également pour le calibrage du modèle concerné, à savoir l’évaluation des critères individuels et la détermination de leurs poids respectifs.

Mots-clé: évaluation multicritères; croisements à niveau; sécurité; coûts; nuisances sonores; influence écologique; modélisation de micro-simulation
Nomenclature
MCA – multi-criteria analysis
AHP – analytical hierarchy process
4W – 4-way intersection (crossroad)
4W+TL – 4-way intersection with traffic lights
3W – 3-way intersection (T-intersection)
3W+TL – 3-way intersection with traffic lights
RA – roundabout
TRA – turbo roundabout

1. Introduction

Multi-criteria assessment (MCA) has accompanied mankind since time immemorial. A decision-making process based on individual selected criteria is performed, consciously or unconsciously, very often. In technical matters, however, this process must be further refined so that based on input data an unambiguous, ideally mathematically identifiable, result may be yielded. Only then is the verifiability and repeatability of a respective process ensured. In the road construction sector, MCA is primarily associated with alternative solutions of individual designs of road routes. This use is desirable mainly in rural areas where individual criteria are relatively easy to quantify. In urban areas, however, road routes assessment is not very useful as the principal limiting element of an urban road network are intersections. The paper addresses the design of a MCA methodology for at-grade intersections, both in urban and rural areas. While in urban areas they should constitute the deciding element related to the designed network, in rural areas this methodology may be implemented as part of the existing assessment methods of individual route alternatives. Unlike the complex assessment of individual routes in rural areas, our focus in the developed methodology is already on a particular element of a road network.

The article is divided into two basic parts. In the first part, the procedure for the MCA application is described, including selected criteria, their weights and the subsequent impact on the developed methodology. A two-level assessment model was used during the MCA application based on which a decision tree was elaborated. The selection of a particular MCA method was modified to fit the presumed implementation of the methodology in a software form. The choice of individual criteria and their weights were subsequently consulted with the professional community to reflect a robust view of the issues.

The second part of the article describes a particular case of the application of the methodology in practice for a selected intersection. The existing two-lane roundabout in Prague 11 in Litochlebske Plaza was chosen as a pilot project. In the light of the current boom of turbo roundabouts, classic two-lane arrangement seems extremely inconvenient, both in terms of safety and capacity. Using the proposed methodology, suitable alternatives are identified and subsequently assessed in the article. The resultant solution obviously cannot serve as the absolute design alternative for the reconstruction of a given intersection, but it can serve as a basic background document for the investor or designer.

2. MCA application in the choice of at-grade intersections

2.1. MCA fundamentals (Department for Communities and Local Government, 2009)

Multi-criteria assessment methods allow us to compare individual alternative solutions using different criteria which are assigned different weights. Virtually all created models are based on this fundamental assumption, nevertheless, they differ in how to handle individual data and how to reach the final assessment which will identify the suitability of a particular alternative for the given input conditions. In technical disciplines, however, MCA methods must ideally be used so that our decisions are only based on measurable and verifiable data and the result may preserve its validity. Thus, in the selection of a suitable method, it was first necessary to identify the requirements that the selected method should meet:
validity and ability to verify input data
relative simplicity of use
possibility of expressing mutual dependences among individual criteria
quantitative expression of individual criteria and their weight
suitability of application for computer processing

The combination of a continuous MCA and analytical hierarchy process (AHP) was used for our analysis.

2.2. MCA alternatives (ČNI, 2007)

According to the demands of technical regulations and general world-wide trends applied in the design of at-grade intersections, the following types of intersections were selected as the basic alternatives:

- 4-way intersection (crossroad) – 4W
- 4-way intersection with traffic lights – 4W+TL
- 3-way intersection (T-intersection) – 3W
- 3-way intersection with traffic lights – 3W+TL
- roundabout – RA
- turbo roundabout – TRA

Despite the somewhat limited number of basic shapes, the number of permutations of individual layout arrangements was enormous. Due to the proposed input parameters, therefore, we identified the basic layout of individual shapes of intersections that would be offered to the users of the methodology as the most suitable ones. Examples of input layouts for crossroads are shown in Fig. 1.

2.3. Decision tree

A decision tree defines the position and relations of individual criteria in the MCA process. In this context, it represents the key element of the whole analysis. Among other things, potential MCA outputs are also evident from a decision tree.

A two-level decision tree (Fig. 2) was created for the needs of our methodology. At the first level, individual alternatives are evaluated using the elimination procedure. Threshold values are set for individual alternatives which must be observed so that the alternative may move up to the second level where evaluation using a selected MCA method is performed. This hierarchic structure considerably reduces the needed number of evaluation processes as it straight away eliminates the alternatives which are unsuitable for technical or operating reasons.
The result of MCA will be the total utility value coefficient; based on this coefficient it will be possible to arrange individual alternatives in the order of preference and identify the most suitable one.

Fig. 2. Decision tree

2.4. Evaluated criteria in MCA

According to their position in the decision tree, the basic input criteria have two principal functions – elimination and evaluation.

Elimination criteria:

Width configuration – this criterion defines us the width layout arrangement of individual legs of an intersection. Based on this criterion, the alternatives that are unsuitable for particular width layout arrangements may subsequently be eliminated.

Intersection capacity – for each type of intersection suitable ranges of traffic volumes for which they are applicable are available. This criterion will constitute a limitation from above, i.e. after the capacity of the evaluated alternative is exceeded the alternative will automatically be eliminated. Preliminary evaluation may be made considering the values specified in the ČSN 73 6102 standard currently in force. (ČNI, 2007)

- uncontrolled intersections max. 2000 veh/h
- intersections controlled by traffic lights max. 6500 veh/h
- roundabouts 1/1 max. 2500 veh/h
- turbo roundabouts max. 4000 veh/h (depending on type and arrangement)
Area parameters – it goes without saying that different types of intersections have different spatial requirements. This criterion will allow the evaluator to define the spatial dimensions of the area which is available (a/b), and, besides, in the case of insufficient spatial conditions the evaluator will be able to individually eliminate the alternatives with too large demands for space in comparison to the spatial conditions available.

Urban/rural environment – this criterion defines the environment in which an intersection is located. It will, in particular, affect intersections with traffic lights which are unsuitable for rural environments. The criterion, however, will also have an essential impact on the weight of individual evaluation criteria.

Evaluation criteria:

Average time delay - this is the value of the average time delay at the critical entry into an intersection. Based on this value, the level of service – LOS is also identified. With respect to the used methodologies, it is not very practical to bind the criterion on LOS as evaluation in relation to the average time delay is more accurate and more objective. Based on the experience from the past and the results of modelling, the mean time delay limit value was identified as 100s. The priority is set from 0.2(100s) to 1.00(5s) with a linear function.

Safety index (Table 1) - the safety index expresses the risk of an accident at a given intersection. The safety of individual types of intersections in the Czech Republic has been the subject of numerous research projects so that safety parameters may be adopted from these studies. The identification of the safety index for individual types of intersections, therefore, relies on the statistical evaluation of the average accident rate of individual types of intersections complemented by the accident rate indicator derived from the number of crossing and merge conflict points (1) (Slabý P., 2005).

\[ I_s = 0.5(I_A + I_C) \]  

\( I_s \) – safety index  
\( I_A \) – index of relative accident rate  
\( I_C \) – index of conflict points influence

Table 1. Safety index for separate intersection types

<table>
<thead>
<tr>
<th>Type</th>
<th>( I_s )</th>
<th>( I_c )</th>
<th>( I_s )</th>
</tr>
</thead>
<tbody>
<tr>
<td>3W</td>
<td>5</td>
<td>8</td>
<td>6.5</td>
</tr>
<tr>
<td>4W</td>
<td>4</td>
<td>3</td>
<td>3.5</td>
</tr>
<tr>
<td>3W+TL</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>4W+TL</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>RA 1/1</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>RA 2/2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>TRA - knee</td>
<td>7</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>TRA – standard/egg</td>
<td>6.5</td>
<td>6.5</td>
<td></td>
</tr>
<tr>
<td>TRA - rotor</td>
<td>5</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

The priority is set from 0.2\((I_s=2)\) to 1.00\((I_s=10)\) with a linear function.

Exhaust fumes/emissions – the criterion defines the volumes of exhaust fumes/emissions produced for individual alternatives. These values will be obtained by means of micro-simulation modelling in the AIMSUN software for the whole traffic system of an intersection. The model will serve for the comparison of mainly CO\(_2\), NO\(_x\) and PM (particulate matter). To make the values comparable regardless of the traffic system size and vehicle volumes, the exhaust fumes will be expressed in g/vehicle/km (Meredith Jackson, Hesham A. Rakha, 2011). For the purposes of this article, only CO\(_2\) and NO\(_x\) emissions have been compared. The priority is set from
0.1(CO$_2$$>$600g/veh/km; NO$_X$$>$1.5g/veh/km) to 1.00(CO$_2$$<$300g/veh/km; NO$_X$$<$0.75g/veh/km) with a linear function.

**Noise pollution** – the criterion expresses the impacts of noise on the surrounding environment. The noise pollution values will be obtained from micro-simulation modelling in the AIMSUN software and the methodology will be modified according to the experience from in-situ measurements (Martin Decký, 2009). For the purposes of this article, based on both foreign and Czech experience, the range of the L$_{A,eq}$ value has been identified between 60dB (Priority=1) and 75dB (Priority=0.2) for individual alternatives. (Claudio Guarnaccia 2010)

**Construction costs** – the criterion expresses the effect of the costs for the construction of an intersection on the total evaluation of the intersection. It must, however, be realised that not all construction related criteria (diversion routes, relocations of utility services etc.) may be considered within this criterion. We may, however, depart from a valid assumption that these costs will be identical or very similar in all alternatives so that they will not be manifested in the resultant evaluation. Construction costs will be expressed by means of aggregated items defined for individual layout elements of an intersection. Based on the initial calculation for several intersections, a linear dependence between € 0 (current state) and € 1.0 mil. (extensive intersection with traffic lights) was defined.

**Operating/running costs** – this criterion will consider the differences among individual alternatives in terms of operating costs. They involve the costs for maintenance, necessary repairs and reconstructions and the costs for consumed power (traffic lights). The criterion, however, will also include the running costs of individual vehicles passing through the intersection, i.e. mainly the differences in their fuel consumption and time economies, but also the costs of delay at the intersection due to accidents. Operating costs for the operation and maintenance of an intersection were not considered for the purposes of this article; nevertheless, the assumption that they will be the highest for intersections with traffic lights is relevant in this respect. The most convenient option in the calculation seems a linear relationship between € 0.12-0.35/veh/km.

2.5. **Weight of criteria**

In assigning the weights to criteria, we relied on the opinions of experts from different fields of expertise in the Czech Republic. To make the identification of weights easier to imagine, it was further subdivided. The weights among individual “pillars” (i.e. Traffic Engineering criteria / Impacts on Environment / Costs) were assigned using the AHP method, while within individual pillars the weights were assigned using the Metfessel allocation. The difference between them, in fact, is only superficial as both methods are based on a similar reasoning logic so that the weight for the calculation itself may be defined using the Metfessel allocation. For better data validity weights were set differently for different surroundings, in which is evaluated intersection located. Four surroundings were defined, whereas three are located in urban area (differences are mainly connected to density of house-building) and one is located in rural area. Evaluated intersection is located in urban area with disperse, mainly residential house building.

The resultant values for a given environment are presented in Table 2.

**Table 2. Weight of criteria**

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Point evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety</td>
<td>34</td>
</tr>
<tr>
<td>Average time delay</td>
<td>20</td>
</tr>
<tr>
<td>Exhaust fumes</td>
<td>13</td>
</tr>
<tr>
<td>Noise</td>
<td>17</td>
</tr>
<tr>
<td>Construction costs</td>
<td>8</td>
</tr>
<tr>
<td>Operating costs</td>
<td>8</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
</tr>
</tbody>
</table>
3. SELECTED INTERSECTION AND ITS ALTERNATIVE DESIGN

3.1. Existing state

The investigated intersection in Litochlebske Plaza (Fig. 3) is located in Prague, the South City district. The intersection has a four-way layout; from the east vehicles enter the intersection along Hviezdoslavova Road, and from the west along Türkova Road. The south entry forms the mouth of Chilská Road, while the north entry is the mouth of Ke Stáčírně Road. It is this very intersection leg that is the only one with a single-lane entry and exit. The entries and exits are separated by dividing strips or island, which are elevated with grass cover.

Fig. 3. “Litochlebske Plaza” roundabout

The circulatory roadway has two lanes along the whole length. In the western and southern leg, an exit lane is added at the exit for the right turn. Places that are to be avoided by vehicles are fitted with traffic stopping shadows and road humps. However, this solution is not ideal and adequate, which is manifested by the condition of the road humps. There is no pedestrian crossing in the whole area of the intersection, only a pedestrian subway at the northern and western entry in the immediate vicinity of the roundabout. The intersection is characterised by large radii of direction curves at entries and exits that lead to higher speeds.

In terms of traffic volumes (Fig. 4), the total volume of vehicles is not much of a problem but rather their distribution into different directions and into individual lanes. Also, the geometric layout arrangement of the intersection allows the passage of vehicles across the intersection at speeds of up to 70 km/h, which is definitely not ideal. The accident rate as compared to single-lane roundabouts is almost double; there are mostly rear-end collisions at the entries to the intersection. Accidents are mainly with material damage; only three people were slightly injured during the three years of monitoring.

Fig. 4. (a) Peak traffic volumes per hour (b) Configuration of lanes
3.2. Design of layout alternatives and their MCA evaluation

Individual elimination criteria will be applied in the preliminary design of alternative layouts. The design is based on the following input parameters of the intersection:

- total traffic volumes at the intersection 2345 veh/hour
- area available 120/120m
- configuration of lanes 2+2/2+2/2+2/1+1 (Fig. 4)
- no pedestrians’ collision flows

Based on the above criteria, an uncontrolled four-way intersection which fails to meet both capacity and traffic lane configuration demands may be eliminated. Then, for a single-lane roundabout we reach the limit value, as the suitable alternative offered here in terms of the traffic lane configuration is a roundabout with bypasses. Among turbo roundabouts, those best choices corresponding to the given configuration are the knee-TRA and classic-TRA type. A potential alternative offered is, naturally, also a 4-way intersection with traffic lights (Fig. 5). These alternatives, however, rely on the construction of the second lane in Ke Stáčírně Road.

![Fig. 5. Design of chosen alternatives](image)

Hence, in the final result, there are five alternatives that may be compared against each other using the MCA method (Uhlík, M., Hradil, J. 2011).

- Alternative 0 – current state
- Alternative 1 – RA with bypasses
- Alternative 2 – knee-TRA
- Alternative 3 – classic-TRA
- Alternative 4 – 4-way intersection with traffic lights

All alternatives have been modelled for the respective distribution of traffic volumes. The results are presented in Table 3.

<table>
<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Current state</td>
<td>2</td>
<td>18</td>
<td>1.00/445.4</td>
<td>64</td>
<td>0.000</td>
<td>0.26</td>
</tr>
<tr>
<td>RA+bypasses</td>
<td>9</td>
<td>8</td>
<td>1.01/394.6</td>
<td>63</td>
<td>0.394</td>
<td>0.21</td>
</tr>
<tr>
<td>knee-TRA</td>
<td>7</td>
<td>5</td>
<td>1.06/407.4</td>
<td>62</td>
<td>0.396</td>
<td>0.20</td>
</tr>
<tr>
<td>classic-TRA</td>
<td>6.5</td>
<td>5</td>
<td>1.12/425.2</td>
<td>62</td>
<td>0.384</td>
<td>0.20</td>
</tr>
<tr>
<td>4W+TL</td>
<td>9</td>
<td>25</td>
<td>1.35/542.8</td>
<td>67</td>
<td>0.395</td>
<td>0.32</td>
</tr>
</tbody>
</table>

The values resulting from the evaluation based on the Metfessel allocation are presented in Table 4. The generated bar chart (Fig. 6) clearly shows the differences between individual alternatives.
3.3. Evaluation of the MCA analysis results

As the MCA evaluation results imply the assessed alternatives were ranked as follows:
1) Roundabout 1/1 with bypasses
2) Knee turbo-roundabout
3) Classic turbo-roundabout
4) Crossroad with traffic lights
5) Current state

In fact, the difference between a roundabout with bypasses and, successively, turbo-roundabouts is not negligible. A roundabout with bypasses certainly is not absolutely suitable everywhere, particularly because of its relatively significant demands for space. Successively, the difference between both turbo-roundabouts is relatively slight resulting rather from a better adjustment of a knee-TRA to existing traffic volumes. The intersection with traffic lights loses points due to relatively high average time delay values though it must be added that this is a typical feature of intersections with traffic lights. Under heavy traffic loading, this fact appears to be rather an advantage as the growth in time delays on intersections with traffic lights is not so dramatic as on uncontrolled intersections and roundabouts. The current state was ranked worst of all, mainly thanks to its highly problematic safety and relatively high time delays (as compared to TRA). This type of roundabout in combination with high traffic volumes also generates relatively high accident rates.
The above results, however, cannot be considered the ultimate design solution. The used weights and the total evaluation were created in cooperation with specialists in individual areas; the micro simulations of individual types of intersections and the successive gauging of models are presently still running. For, if we, for example, look at the distribution of individual weights (Table 2), the absolute predominance of safety over the other factors is quite evident. Therefore, sensitivity analysis must be made to balance correctly the weights and the evaluation of the corresponding parameters so that the methodology may yield the optimum results.

4. Conclusion

The MCA application for the selection of a suitable technical design solution in urban as well as rural areas, if based on a verified methodology and valid input values, appears to be of significant contribution for both designers and investors or the state administration authorities. Despite this, we cannot claim that this methodology may totally replace the assessment of a specific design solution in a given locality. This, above all, results from the multiple factors that simply cannot be considered in the methodology (e.g. utility routes, coordination with other intersections, etc.). The methodology will be applicable mainly in the initial design phase where based on input data the characteristics of individual alternative solutions, their advantages and disadvantages and their order of preference based on predefined weights may be identified. Among relatively great benefits of the methodology are its easy applicability and the computer processing option. Also, the methodology is applicable not only in the Czech Republic, but also abroad as the basic traffic engineering principles are, at least in Europe, largely similar, and thus there is no need for major changes in the methodology. In the future, we presume that the methodology may be used mainly in cooperation with the state administration authorities which may determine the suitability of a solution proposed by a designer based on the basic input data. The applicability in design practice is directly bound on this; for investors the methodology may seem a fairly effective tool for the assessment of economic benefits of a proposed solution applying the operational and economic evaluation method. Overall, the methodology represents a simple and versatile tool, which should contribute to ideal intersection design, both in rural and urban area.

Acknowledgements

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References

ČNI (2007), ČSN 73 6102 – Design of road intersections, ČNI, Praha, ČR.


Slabý P. (2005), Issues of objective evaluation of road traffic safety, project GA ČR 103/02/0065, FSv, ČVUT v Praze.


Claudio Guarnaccia (2010), Acoustical Noise Analysis in Road Intersections: a Case Study, RECENT ADVANCES in ACOUSTICS & MUSIC.

Martin Decký (2009), Noise Pollution from Roundabout Traffic in the Outer Environment of Built-up Areas of Towns, Perners contacts, elektronický časopis University of Pardubice, IV. Volume, ISSN 1801-674X, s. 53-68.