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COMPARISON OF DESIGN VARIANTS FOR ROUNDABOUT RECONSTRUCTION USING AHP METHOD – CASE STUDY

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Abstract: Traffic intersections are considered to be the most complex and the most demanding points where several traffic streams intersect. The paper presents the reconstruction analysis of the large urban three-lane roundabout Jadranska Avenue - Dubrovnik Avenue located in the City of Zagreb (Croatia). The goal of this study is to find the optimal traffic-technical and urban solution in a scope of road safety using multi-criteria decision-making procedure. Current traffic conditions and problems regarding the capacity and road safety are presented. Three developed conceptual solutions have been also used and analysed. The collected data show the reasons why local municipality wants to bring the roundabout into the condition of efficient capacity and road safety. The present work describes applying the multi-criteria analytical hierarchy process (AHP) method to evaluate roundabout design variants through differential weighting of various criteria and subcriteria with emphasis on road safety. For solving the multi-criteria analysis the Expert Choice software package has been used. This approach may prove useful for evaluating and selecting appropriate roundabout designs for this and other contexts.

Keywords: roundabout, road safety, design variants, analytic hierarchy process

1. INTRODUCTION

Compared with traditional at-grade urban road intersections with or without traffic lights, appropriately dimensioned, designed and modelled roundabouts greatly increase the level of efficiency, i.e. the capacity and level of service [1,2]. From the economic standpoint, roundabouts bring numerous benefits: lower land purchase costs, lower cost

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of construction and installation of traffic equipment, less costly maintenance, and lower losses generated by congestions due to excessive traffic volumes [3]. Specially, the level of traffic safety increases considerably when roundabouts are used [4,5].

The main purpose of the study was to study, describe and analyse current state and to select the optimal design solution for the reconstruction of a large three-lane roundabout located in the City of Zagreb (Croatia). This study involved a thorough review of the relevant literature. Results and recommendations of Legac et al. [6] were used as a basis for this study.

The first section summarizes previous studies and presents basic roundabout design geometry and traffic flow characteristics with emphasize on traffic safety level. The second section describes proposed design variants. The third section describes the development and application of AHP structure for evaluating three alternative design variants to achieve higher traffic safety level. The fourth section discusses the results and draws final conclusions.

2. BASIC DATA ABOUT ROUNDABOUT JADRANSKA AVENUE - DUBROVNIK AVENUE

The Jadranska Avenue – Remetinečka Avenue – Avenue Dubrovnik – Jadranski Bridge roundabout is located at the south-western entry into the City of Zagreb (Croatia), opened to traffic in 1985. Before reconstruction it was designed as a signalized at-grade intersection, with grade-separated pedestrian traffic and with no tram traffic. Fast urbanisation, insufficient number of bridges spanning the Sava River, and increased traffic volumes of the south-western city entry influenced increased traffic volumes of the traffic network. With the aim of increasing the level traffic safety, capacity and introducing tram traffic to the intersection, a roundabout was constructed as the most suitable solution at the upper level, and pedestrian paths and trams with relief tracks at the lower level.

2.1. Design geometry and volume

Roundabout is located in the flatland without any major limitations, whereas four tangential approaches (1-Jadranska Avenue, 2-Remetinečka Road, 3-Avenue Dubrovnik and 4-Jadranski Bridge) are at longitudinal slope of 1% to 3%. The roundabout inscribed circle diameter (D_v) is 148 m and central island diameter (D_u) is 124 m (Figure 1). The circulatory roadway has three lanes each 4,0 m wide. Approaches are designed with three lanes each 3,5 m wide. Entry approach radius are 80 m except for the northern approach, which has radius of 200 m. The circulatory roadway has a 2% slope towards the centre because of the drainage [6–8].

The latest measurable traffic volume was collected on 24 October 2008 (Table 1). Registered value of roundabout traffic volume ranges from 90.000 to 100.000 [veh/day], where Q_k = 99.023 [veh/day] has had more pronounced volumes on all approaches except on approach 2 [8].

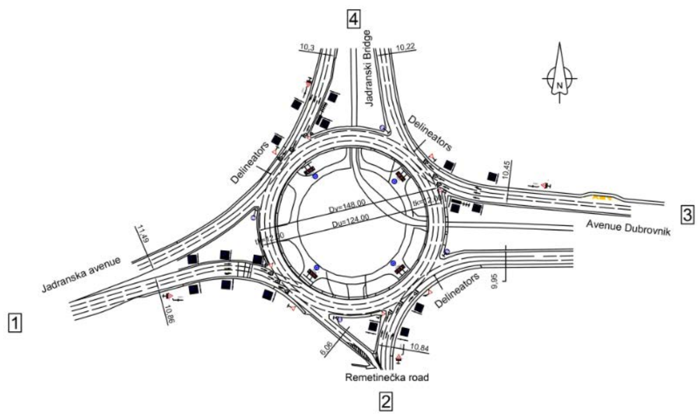

Figure 1. *Design geometry of the roundabout Jadranska Avenue – Avenue Dubrovnik* [6]

Table 1. *Average annual daily traffic at Jadranska Avenue – Avenue Dubrovnik roundabout* [8]

Average annual daily traffic (AADT) – 24.10.2008.				
Approach	**Movement of vehicles**			
	Right	**Straight**	**Left**	**Σ**
1. Jadranska Avenue	11	11.060	12.817	23.888
2. Remetinečka Road	3.928	7.126	20	11.074
3. Avenue Dubrovnik	24.647	8.344	1.513	34.504
4. Jadranski Bridge	12.975	4.575	12.007	29.557
			TOTAL	***99.023***

2.2. Safety

The level of traffic safety was analysed by video recording, and on the analysis of the approach speeds, sight distance and traffic equipment installation. This results have been published in the earlier papers [6,7,9]. However, because of the study purpose, the collision diagram has been presented (Figure 2), and the official data of the Ministry of Interior, Traffic police for the period from 2001 to 2010 have been processed and analysed [10]. Unfortunately, detailed data compiled by the traffic police from 2011 to 2014 was not available. But, from [11] one could conclude that from 2011 to 2013 there were in total 290 accidents. Table 2 shows the total number of accidents per years of occurrence, per number and types of accidents, and per number of the injured per years and types of accidents. The observed period shows that the most usual types of accidents are: (1) rear-end collisions accounting for as many as 1.185 accidents, or 60,46% out of the total number of accidents in which 111 persons were injured or 59,04% of the total number of the injured; (2) failure to yield at entry (entering-circulating) accounting for 506 incidents or 25,82%, with 39 injured or 20,75% of the total number of the injured.

Other types of incidents have caused only 41 or 2,0% of accidents, in which 12 persons were injured or 6,38% of the total number of the accidents.

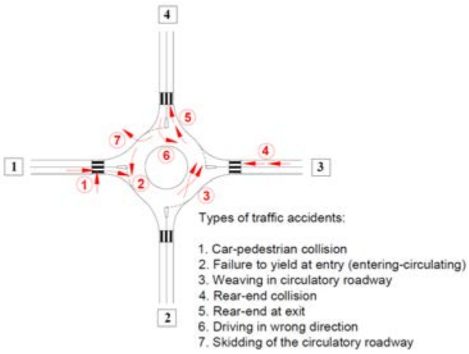

Figure 2. *Roundabout collision diagram* [7]

The design solution with tangential merging of three-lane approaches provides an additional cause and reason for reduced capacity and safety component of the entire intersection. With the help of radical reconstruction, in new urban, commercial and spatial intersection surrounding, it is necessary to achieve optimal design solution. So, six proposed reconstruction design solutions with particular focus on the safety-capacity and design geometry and their correlation are presented in next chapter.

3. RECONSTRUCTION VARIANTS

3.1. Variant 1

In order to improve the level of traffic safety and capacity, a variant reconstruction design (*Variant 1*) was proposed by Šubić [12]. Design consists of spatial and traffic improvement. Step I – approach verticalisation, channelling of vehicles and elimination of the external lane. This is to achieve spatial – time distances between approaches, adding one more lane for right turns because of increased traffic flow volumes of right-turners at approaches 3 and 4. Step II – follow-up of step I regarding the construction of the overpass in the East-West and West-East direction, with grade difference from the current condition in the inter-phase by 5,50 m and the length of approach ramps of 180-200 m to overcome the climb of 4% and extension regarding widening of the approaches 1 and 3 due to the construction of the overpass (Figure 3.a) [12].

3.2. Variant 2

The Faculty of Civil Engineering from the University of Zagreb and AKING d.o.o. propose four design variants:

- *Variant 2* traffic flows West – East are guided over viaducts at +2 level
- *Variant 3* traffic flows West – East are guided through tunnels at -1 level
- *Variant 4* traffic flow West – North is guided over viaduct at +2 level, traffic flow North – East is guided through the tunnels at -1 level
- *Variant 5* traffic flow North – East is guided through tunnel at -1 level [8].

Table 2. *Number of accidents and injured according to the types of traffic accident* [10]

NUMBER OF ACCIDENTS ACCORDING TO TYPE OF ACCIDENT						
Year	Number of accident	2. Failure to yield at entry	3. Weaving in circulatory roadway	4. Rear-end collision	6. Driving in wrong direction	7. Skidding of the circulatory roadway
2001	349	49	26	269	0	5
2002	313	52	20	234	0	7
2003	354	106	26	206	0	10
2004	248	37	24	179	0	5
2005	136	48	12	67	0	6
2006	129	48	15	57	0	4
2007	124	46	11	58	0	4
2008	104	28	20	46	0	3
2009	119	49	13	44	4	2
2010	84	43	8	25	2	1
Sum	1960	506	175	1185	6	47
Percentage [%]		25,8	8,9	60,4	0,3	2,3
NUMBER OF INJURED ACCORDING TO THE TYPES OF ACCIDENT						
Year	Number of accident	2. Failure to yield at entry	3. Weaving in circulatory roadway	4. Rear-end collision	6. Driving in wrong direction	7. Skidding of the circulatory roadway
2001	26	4	0	20	0	2
2002	11	3	0	6	0	0
2003	29	6	2	15	0	5
2004	18	4	1	11	1	1
2005	13	2	1	5	0	3
2006	22	2	0	17	0	2
2007	19	3	0	11	0	2
2008	14	2	0	11	0	0
2009	23	6	1	12	1	1
2010	13	7	2	3	0	1
Sum	188	39	7	111	2	17
Percentage [%]		20,7	3,7	59,0	1,0	9,0

Brief description of variant main characteristics is presented in following. Analysing the financial aspects of construction, space occupancy and capacity increase, as optimal design variant *Variant 3* (Figure 3.b) was selected by authors [8]. Apart from the construction of a tunnel at the level -1, *Variant 3* proposes the keeping of three lanes in the circulatory roadway and introducing traffic lights at basic roundabout layout. Also, the tangential segregation of the right turners that has already been achieved by the installation of grade separators in 2001 has been proposed on all approaches.

3.3. Variant 6

The final variant design was proposed by Vukušić (Figure 4) [13]. Design consists of Phase I and Phase II. Phase I - approaches are verticalised, right turners are channelled at all approaches except for the approach Jadranska Avenue, the northern and southern roadways of Jadranska Avenue are spaced out, and the number of lanes on its southern part is reduced. This is due preparation for digging of the tunnel in the next phase. The roundabout approaches are designed with radius 20 m to enable merging of long vehicles. The number of traffic lanes in circulatory roadway is reduced in order to increase the level of traffic safety. The right turners are physically segregated at all approaches except on approach 1, and because of the increased traffic flow volume, one traffic lane is added at approach 3 and 4.

The second phase of reconstruction consists of the construction of two tunnel pipes in the East-West and West-East direction, and the construction of the overpass from the North towards the East. The length of the ramps for entering and exiting from the tunnels is about 150 m with a decline of 4%. The tunnels are located at 5,5 m below the level of the trams that pass below the roundabout. The overpass is constructed from the approaching and exiting ramps with a gradient of 4% that are about 150 m long and a horizontal section which is elevated 5,5 m above the roundabout. For easier merging of the vehicle from the overpass from the North, those from the tunnel from the West, and the segregated right turners from the South to the Avenue Dubrovnik, the eastern exit from the roundabout should be closed [13].

a) Layout of Variant 1 b) Layout of Variant 3

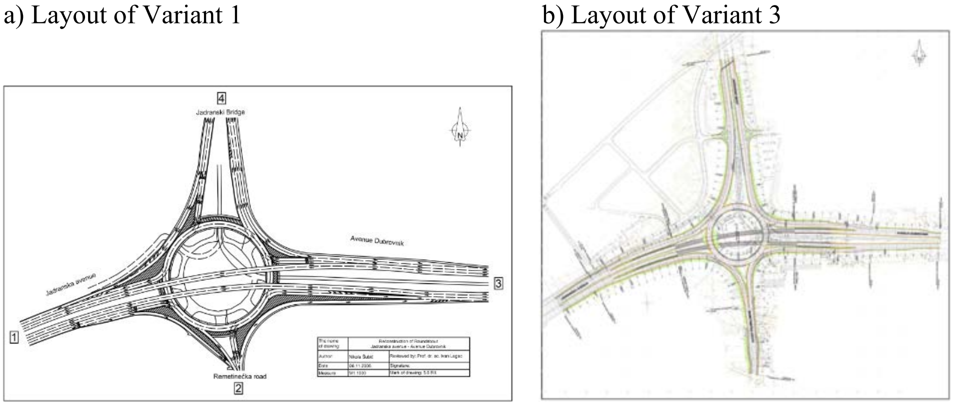

Figure 3. *Layout Variants; a) Variant 1 according to* [12]*, b) Variant 3 according to* [8]

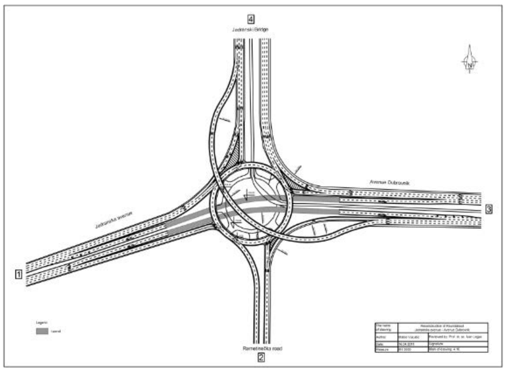

Figure 4. *Layout of Variant 6 according to* [13]

4. USING THE AHP TO EVALUATE AND SELECT THE OPTIMAL DESIGN

4.1. The AHP methodology

Thomas Saaty developed the AHP method to guide complex multi-criteria decision making (MCDM) problems. 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 [14]. According to Saaty [15], in order to define the relative importance of criteria and subcriteria with respect to the objective of research, criteria are ranked using a scale, (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. A consistency index (CI), which indicates the deviation or degree of consistency was defined. If the Consistency Ratio (CR) is smaller or equal to 10%, the inconsistency is acceptable, and if the CR is greater than 10%, the preference needs to be revised.

4.2. The AHP model

A theoretical framework for reconstruction design was defined including relevant road design parameters extracted from the research literature [6,7,9,14]. These parameters constituted five criteria and associated subcriteria (Figure 6) that were used to evaluate six alternative reconstructions of the Jadranska Avenue – Avenue Dubrovnik roundabout. These parameters were mainly defined by authors [6] but here we are more focusing on traffic safety. According to Pilko [16] traffic safety criteria could consists here of two subcriteria. The subcriterion of number of conflict points was selected in order to compare number of conflict points of proposed design variants. The subcriterion traffic accidents was derived from predicted number and consequences of traffic accidents that will occur concerning proposed design variants. From the analysed literature, weighting functions for objectives, criteria and alternatives based on the Saaty scale have been generated. After criteria were selected, analysed and ranked, data were entered and processed in the software *Expert Choice 11.5*.

The highest weighting coefficient (.272) was associated with the *Safety* and *Ecological* criterion, while the lowest coefficient (.123) was associated with the criterion *Reconstruction of land facilities*. The low inconsistency among observed criteria (.04) suggested a well-structured model (Figure 5).

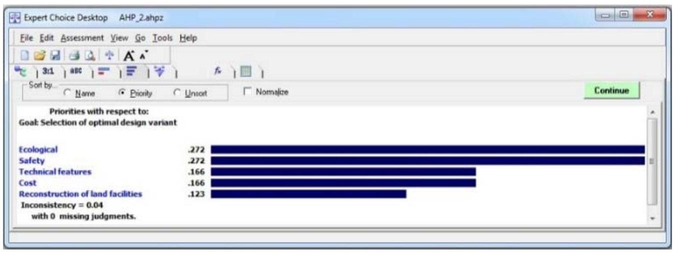

Figure 5. *Criteria priorities*

4.3. Results of the AHP method

Assessment of subcriteria and proposed alternatives was also carried out using *Expert Choice 11.5*. In the determination of the importance of *Technical features* criteria, the highest weighting coefficient (.750) was assigned to the subcriterion *Route facility complexity level*, and the smallest weighting coefficient (.250) to the subcriterion *Route design complexity level*. Overall CR of the model was 0% indicating a well-structured model. In determining ecological impact, the subcriterion *Level of traffic noise* received the highest weighting coefficient (.500) and the subcriterion *Level of land occupancy* and *Spatial-urban planning influence* the lowest (.250). Overall CR of the model was 0%, again indicating a well-structured model. In the determination of costs, the subcriterion *Construction costs* received the highest weighting coefficient (.900) and the subcriterion *Land purchase* the lowest (.100). Overall model CR was again 0%. During assessment of traffic safety, bouth subcriteria were found to be correlated and therefore were ranked as equally important. For this reason, total inconsistency of the model was 0%. The results of the AHP modeling, together with weighting of all criteria and subcriteria, are shown in Figure 6.

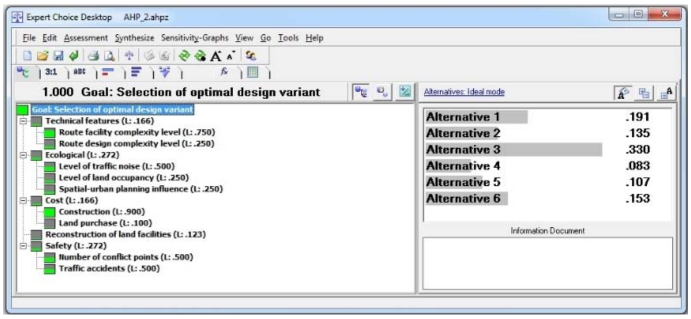

Figure 6. *Weighting factors for criteria and subcriteria in the AHP model*

Using the AHP method and the simulation software *Expert Choice 11.5* one can conclude that optimal reconstruction design variant for Jadranska Avenue – Avenue

Dubrovnik roundabout is *Variant 3,* with weighting factor of (.330) as shown in Figure 7.

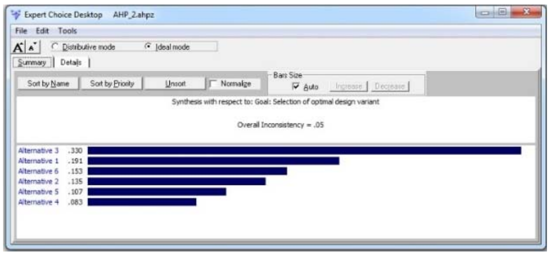

Figure 7. *Weighting factors and ranking of alternatives*

5. DISCUSSION AND CONCLUSION

By using the AHP method to assess a large number of alternatives on the basis of comprehensive parameters one could 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 reconstruction design of a large urban roundabout located in the City of Zagreb.

Of the five criteria selected for the AHP model, the most important was *Safety and Ecological*, and the least important was *Reconstruction of land facilities*. Inconsistency among the observed criteria was (.04), indicating that the model was well structured. Inconsistency was similarly low for AHP structures of subcriteria, among which *Route facility complexity level*, *Level of traffic noise*, and *Construction cost* were most important, while *Route design complexity level*, *Level of land occupancy*, *Spatial-urban planning influence* and *Land purchase* were least important. From the traffic safety standpoint, *Variant 3* proved to be an optimal reconstruction design solution.

Future studies should examine whether this approach works on urban roundabouts of different types and with other traffic dynamics. Our choice of parameters combined the factors most frequently used to evaluate projects, such as cost, safety, and ecological impact [17–19] together with general civil focused parameters. While these civil focused parameters may limit the generalisability of our AHP model, it may be possible to supplement them with traffic-related ones, such as level of service (capacity, degree of saturation, average delay and queue delay) as is done by Pilko in [16].

This study featured several limitations. One was that collected traffic flow data turned out to be inadequate for assessing the level of service, preventing us from simulating micro and macro aspects of traffic movements and flow using such tools as PTV Visum or similar. Future studies should address these issues. Future work should also conduct a comprehensive survey of road traffic engineering experts and consider perspectives of other stakeholders, such as civil engineer, economist, ecologist, or urban planner. Another survey should be conducted among local inhabitants in order to assess their opinion concerning spatial-urban influence of the proposed design on the studied area. This input may significantly alter the choice and weighting of criteria and subcriteria, which may affect the recommended roundabout design.

The proposed AHP model structure may help policy makers select appropriate roundabout design variants and related road projects for implementation.

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