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# IMPROVED APPLICABILITY DIAGRAM OF TWO-LANE ROUNDABOUTS

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## Abstract

When reconstructing existing or constructing completely new intersections, the main problem is determining the type of future intersection. Capacity is one of the key indicators that influence the choice of traffic control type. In this paper, using different scenarios of theoretical traffic flow distributions and traffic volume scenarios, the authors have determined the applicability area of two-lane roundabouts. The results obtained were used to improve the existing applicability diagrams of the various intersection types presented in several issues of US Highway Capacity Manuals (US HCM). Capacity in each scenario is determined using HCM 2010 and Hagring methods with practically obtained values of the time gap acceptance parameters.

*Keywords: two-lane roundabouts, capacity, gap-acceptance parameters, HCM 2010, Hagring*

## 1 Introduction

In order to determine type of control of future (planned) intersection, based only on traffic demands or capacity, engineers can use applicability diagrams suggested in the US Highway Capacity Manual 2000 (HCM 2000) (Figure 1) [1] or in the newer edition called Planning and Preliminary Engineering Applications Guide to the Highway Capacity Manual 2016 (Figures 2 and 3) [2]. Although capacity is not the only criteria on which this decision should be made, it is the most proper regards to the desired level of service. Other relevant factors are space availability, type of adjacent intersections, environmental impact etc.
The capacity of one intersection is not an absolute category and highly depends on traffic flow distribution between different approaches. Based on HCM 2000 roundabouts are desirable solutions when major and minor streets have approximately equal traffic volume (Figure 1). Other traffic combinations are not detailed explained. In the new version of Highway Capacity Manual (HCM 2016) two different diagrams, depend on different traffic distribution, are proposed when it comes to roundabouts applicability. Furthermore, these diagrams recommend separately one-lane and two-lane roundabouts.
According to these diagrams, one-lane roundabouts are the right solution for almost every traffic volume combinations. It can be applied for major traffic volume between 500 and 1.600 (1.900) veh/h while minor traffic volume is up to 800 veh/h. At the same time, two-lane roundabouts can be applied for major volume higher than 1.050 (1.400) veh/h. Both types of roundabouts have limited application to conditions of a lower major (up to 1.000 veh/h) and minor (up to 500 veh/h) volumes. Under these conditions two-way stop intersection is highly preferred over all other types of intersection control. This can be related to the

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USA local policy and long-term familiarity with this type of intersections. Drivers are more accustomed to STOP sign-controlled intersections instead of roundabouts.
It is clear that applicability diagrams for several types of intersections in different HCM editions differ significantly. They differ not only in detail (roundabouts are far more present in the newer version) but also in traffic volumes to which roundabouts may apply. Because their application highly depends on traffic distribution, these diagrams have to be updated and expanded for more traffic volume combinations and capacity values.

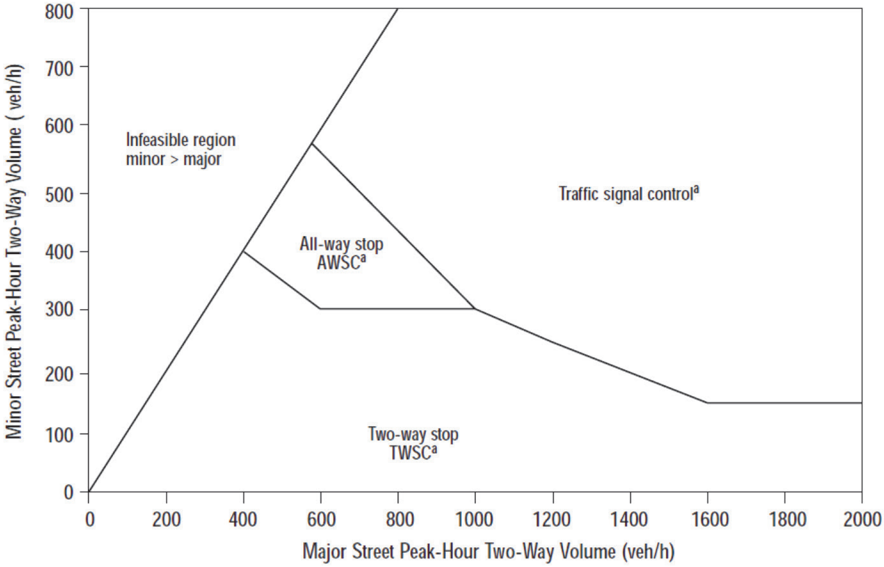


**Figure 1** Intersection control type and peak-hour volumes (a. Roundabouts may be appropriate within portion of these ranges) [1]

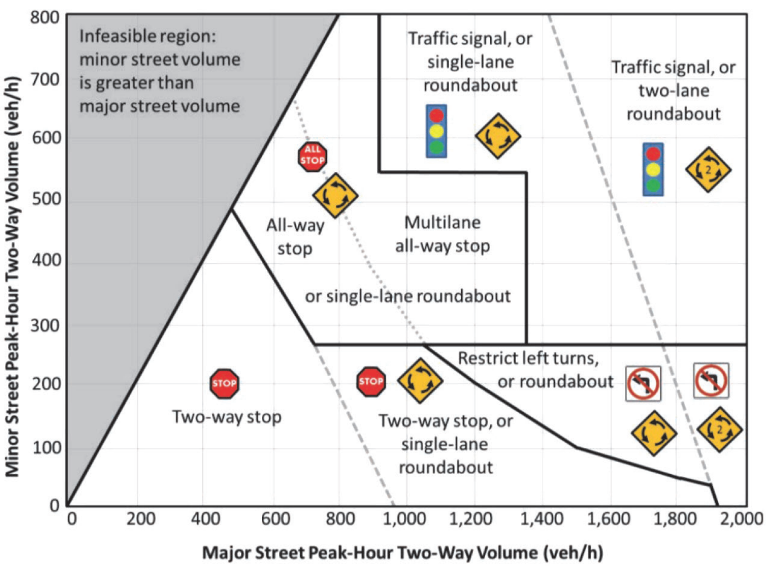


**Figure 2** Intersection control type by peak hour volume - 50/50 Volume Distribution on Each Street [2]

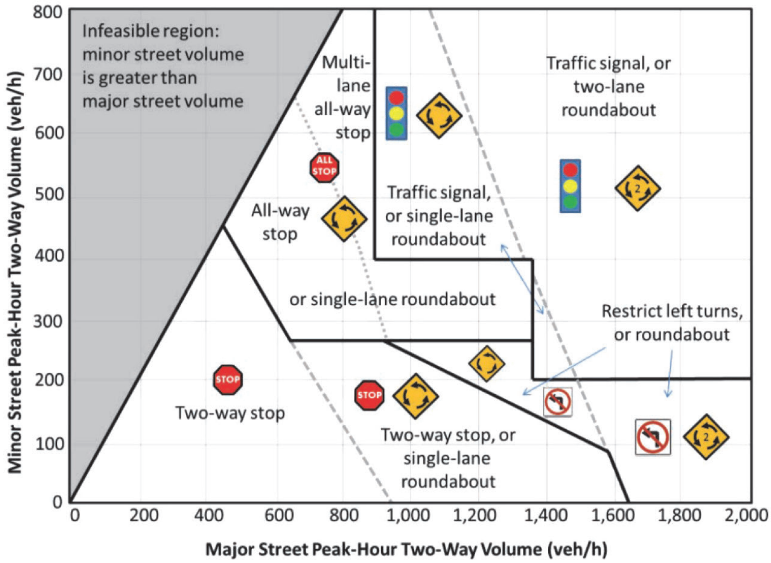


**Figure 3** Intersection control type by peak hour volume - 67/33 Volume Distribution on Each Street [2]

## 2 Capacity calculation methods

Capacity calculation of any type of roundabout can be performed with different empirical regression and gap-acceptance based methods. Empirical regression methods are based on experiences of built roundabouts and their geometric and traffic conditions. Contrary to this, gap-acceptance methods represent a fully theoretical method. Two parameters are essential for this method: critical gap ($t_c$) and follow-up headway ($t_f$).

In this research, two analytical methods were used. First, Hagring method [3], is developed on conflict theory of traffic streams at roundabouts entries. Second, HCM 2010 method [4] can be consider as semi-analytical, but in this paper is calibrated with field obtained gap-acceptance parameters. Definitions, field investigation and calculation methods of critical gap and follow-up headway are not explained in detail in this paper. Instead, we refer to [5], [6] and [7].

In 1998, Hagring [3] proposed a complete formula for the capacity calculation that can be used for each multi-lane intersection. Driver behaviour is represented with a different set of gap-acceptance parameters on each conflict of entry lane and circular lane inside the roundabout. A common assumption is that gaps between vehicles in the circular lane have Cowan's M3 distribution which leads to the following Hagring's capacity equation:

$$C = \frac{e^{\left(-\sum_{i \in I_k} \lambda_i \cdot (t_{c,i} - \Delta_i)\right) \cdot \sum_{i \in I_k} \lambda_i}}{1 - e^{\left(-\sum_{i \in I_k} t_{f,i} \cdot \lambda_i\right)}} \cdot \prod_{i \in I_k} \frac{\alpha_i}{\alpha_i + \lambda_i \cdot \Delta_i} \qquad (1)$$

Where are:

C - capacity of entry lane (veh/h),
α - proportion of free vehicles,
$t_{c,i}$ - is the critical gap for each entry lane (s),
$t_{f,i}$ - follow-up time for each entry lane (s),
Δ - minimum headway of circulating vehicles (s),
$\lambda_i$ - Cowan's M3 parameter,
k - minor flow index,
$I_k$ - set of major flows i that conflict with minor flow k.

For capacity calculation of two-lane roundabout previous equation can be expressed in more simple form: equation (2) for the conflict of one circular lane and one entry lane and equation (3) for the conflict of two circular lanes and one entry lane.

$$C = \frac{q \cdot \alpha \cdot e^{\left[-\lambda \cdot (t_c - \Delta)\right]}}{1 - e^{(-\lambda \cdot t_f)}} \quad (2)$$

$$C = \frac{e^{\left\{-\left[\lambda_1 \cdot (t_{c,1} - \Delta_1) + \lambda_2 \cdot (t_{c,2} - \Delta_2)\right]\right\}} \cdot (\lambda_1 + \lambda_2) \cdot \alpha_1 \cdot \alpha_2}{1 - e^{\left[-(t_{f,1} \cdot \lambda_1 + t_{f,2} \cdot \lambda_2)\right]} \cdot (\alpha_1 + \lambda_1 \cdot \Delta_1) \cdot (\alpha_2 + \lambda_2 \cdot \Delta_2)} \quad (3)$$

Parameters α, λ and Δ are the parameters of the Cowan's distribution. Parameter λ can be expressed by the following equation:

$$\lambda = \frac{\alpha \cdot q}{1 - \Delta \cdot q} \quad (4)$$

while α is represented as Tanner's model:

$$\alpha = 1 - \Delta \cdot q; \quad \Delta = 2\,\text{sec} \quad (5)$$

The greatest advantage of this method is its lane by lane approach, which makes it suitable for multi-lane roundabouts or some special modification of standard types of roundabouts (e.g. turbo-roundabouts). For this purposes, it is necessary to make field measurements for every pair of entry lane and circular lane. For example, a two-lane roundabout with two-lane approach requires four different sets of gap-acceptance parameters.
HCM 2010 methodology is widely accepted and used method for capacity calculation. It is also an analytical method but with some data based on US experience on roundabouts. However, it can be calibrated with local gap-acceptance values. The capacity formula for two-lane roundabouts is given separately for the right (equation 6) and the left (equation 7) entry lane:

$$C_{e,R,pce} = 1130 \cdot e^{(-0{,}70 \cdot 10^{-3}) \cdot v_{c,pce}} \quad (6)$$

$$C_{e,L,pce} = 1130 \cdot e^{(-0{,}75 \cdot 10^{-3}) \cdot v_{c,pce}} \quad (7)$$

These two equations can be expressed in more general form (equation 8) which allows its calibration. Critical gap and follow-up headway can be used as part of equations 9 and 10.

$$C = A \cdot e^{(-B \cdot v_c)} \quad (8)$$

$$A = \frac{3600}{t_f} \quad (9)$$

$$B = \frac{t_c - \frac{t_f}{2}}{3600} \quad (10)$$

Fully description of the HCM methodology for the capacity evaluation of roundabouts can be found in HCM 2010: chapters: 21. Roundabouts, and 33. Roundabouts Supplemental.

When it comes to traffic distribution pattern and its influence on capacity, one more thing is significant for two-lane roundabouts. At least two approaches should be double lane on two-lane roundabouts. This geometric characteristic means that vehicles can use both right and left lane before entering the roundabout. Traffic distribution between these two lanes is often unequal because most drivers use right entry lane and outside circular lane, no matter which exit they will take. This is due to safety uncertainty when driver wants to exit from the inner circular lane, especially if that exit has only one lane. In practice, this misbalance is often ignored. HCM 2010 gives too simple recommendations which in most cases lead to 53-47 % traffic distribution in favour of the right lane. However, HCM approach is used in this paper for the sake of simplification of numerous capacity calculation.
In both methods, local and field-determined gap-acceptance values were used (Table 1). These values are obtained in our previous researches and have been published in paper [8].

**Table 1** Table 1. Gap acceptance parameter for two-lane roundabout [8]

| **Left entry lane** | | | | **Right entry lane** | | | |
|---|---|---|---|---|---|---|---|
| **Inner circular lane** | | **Outside circular lane** | | **Inner circular lane** | | **Outside circular lane** | |
| $t_c$ (sec) | $t_f$ (sec) | $t_c$ (sec) | $t_f$ (sec) | $t_c$ (sec) | $t_f$ (sec) | $t_c$ (sec) | $t_f$ (sec) |
| 3,84 | 2,92 | 3,84 | 2,92 | 2,80 | 2,60 | 3,26 | 2,97 |

## 3 Capacity evaluation based on different traffic flow distribution

Using both described methods capacity was calculated for the standard type of four-leg two-lane roundabout (Figure 4). Different traffic flow distribution scenarios were used. In total, seven theoretical traffic conditions were implemented as origin-destination matrices (Figure 5). Elements of these matrices are the percentage of each traffic movement between two approaches. In every scenario, major and minor traffic flow started from 200 veh/h with step of 200 veh/h. The upper limit for both flows was 1.000 veh/h or when the degree of saturation was above 0,90. This leads to 60-80 capacity values for every scenario. Major or minor flow represent the sum of traffic volume on two approaches, and U-turns were not considered.
Seven scenarios were chosen in order to cover most of the usual distribution of traffic movements. In scenario 1, traffic volume is equally distributed on all approaches. Scenarios 2 and 3 have dominant through movement on all approaches, which is typical for arterial roads. In scenarios 4, 5 and 6 major flows are retained as in the previous ones, while minor approaches have dominant right movement excluding left (scenarios 4 and 5) or through movement (scenario 6). These situations are common, for example, near shopping centres. In scenario 7 both major and minor approaches have dominant right movement.
Detailed results of the capacity calculation for each scenario and traffic combination will not be presented. All results are summarized and presented in the form of applicability diagrams (Figures 6, 7 and 8). The upper limit for capacity calculation under different traffic flow distribution is set at volume to capacity (v/c) ratio of 0,90.

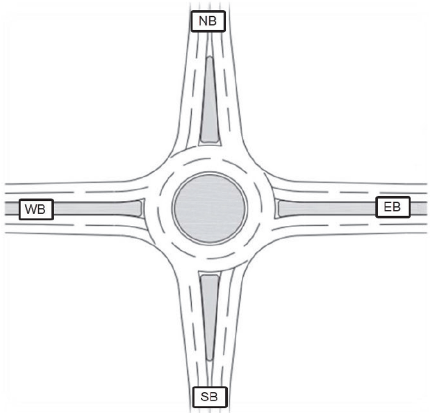


**Figure 4** Two-lane roundabout

| | Scenario 1 | | | | Scenario 2 | | | | Scenario 3 | | | | Scenario 4 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **WB** | **EB** | **SB** | **NB** | **WB** | **EB** | **SB** | **NB** | **WB** | **EB** | **SB** | **NB** | **WB** | **EB** | **SB** | **NB** |
| **WB** | 0 | 0.33 | 0.33 | 0.33 | 0 | 0.7 | 0.15 | 0.15 | 0 | 0.8 | 0.1 | 0.1 | 0 | 0.80 | 0.10 | 0.10 |
| **EB** | 0.33 | 0 | 0.33 | 0.33 | 0.7 | 0 | 0.15 | 0.15 | 0.8 | 0 | 0.1 | 0.1 | 0.80 | 0 | 0.10 | 0.10 |
| **SB** | 0.33 | 0.33 | 0 | 0.33 | 0.15 | 0.15 | 0 | 0.7 | 0.1 | 0.3 | 0 | 0.6 | 0.00 | 0.50 | 0 | 0.50 |
| **NB** | 0.33 | 0.33 | 0.33 | 0 | 0.15 | 0.15 | 0.7 | 0 | 0.1 | 0.3 | 0.6 | 0 | 0.50 | 0.00 | 0.50 | 0 |

| | Scenario 5 | | | | Scenario 6 | | | | Scenario 7 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **WB** | **EB** | **SB** | **NB** | **WB** | **EB** | **SB** | **NB** | **WB** | **EB** | **SB** | **NB** |
| **WB** | 0 | 0.8 | 0.1 | 0.1 | 0 | 0.8 | 0.1 | 0.1 | 0 | 0.30 | 0.60 | 0.10 |
| **EB** | 0.8 | 0 | 0.1 | 0.1 | 0.8 | 0 | 0.1 | 0.1 | 0.30 | 0 | 0.10 | 0.60 |
| **SB** | 0 | 0.8 | 0 | 0.2 | 0.2 | 0.8 | 0 | 0 | 0.10 | 0.60 | 0 | 0.30 |
| **NB** | 0.8 | 0 | 0.2 | 0 | 0.2 | 0.8 | 0 | 0 | 0.60 | 0.10 | 0.30 | 0 |

**Figure 5** Traffic flow distribution scenarios

On the applicability diagrams, two different zones are marked:

- Green zone – two-lane roundabout can be applied regardless of the capacity calculation method and traffic scenario,
- Blue zone – two-lane roundabout can be applied conditionally, which means that for some scenarios and calculation method degree of saturation is higher than 0,90
- Field data for one two-lane roundabout operating in Sarajevo were used to compare those w

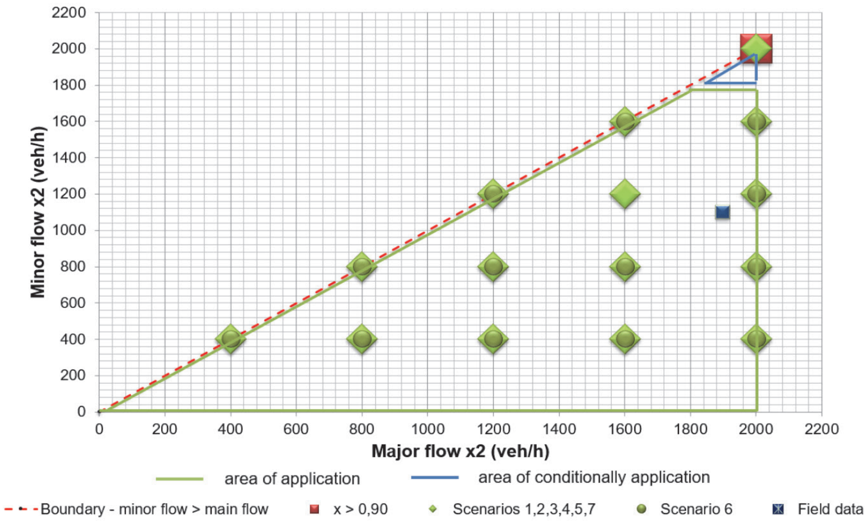


**Figure 6** Applicability of two-lane roundabout based on HCM methodology

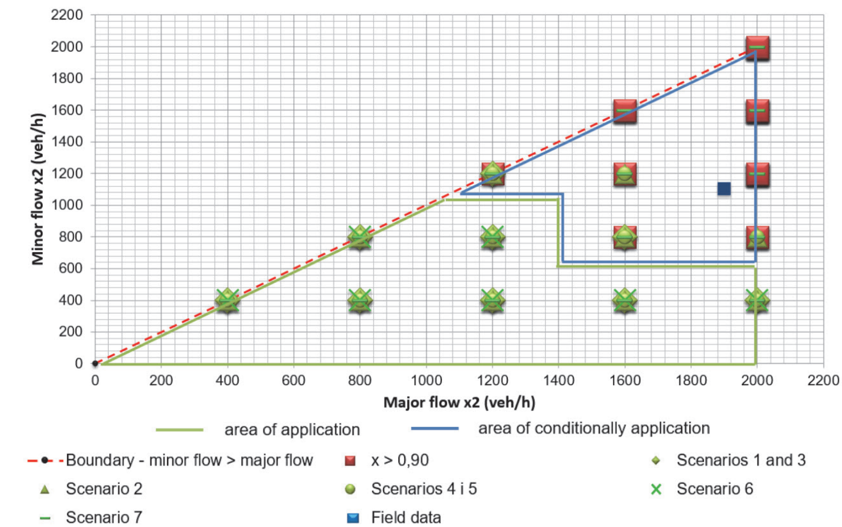


**Figure 7** Applicability of two-lane roundabout based on Hagring methodology

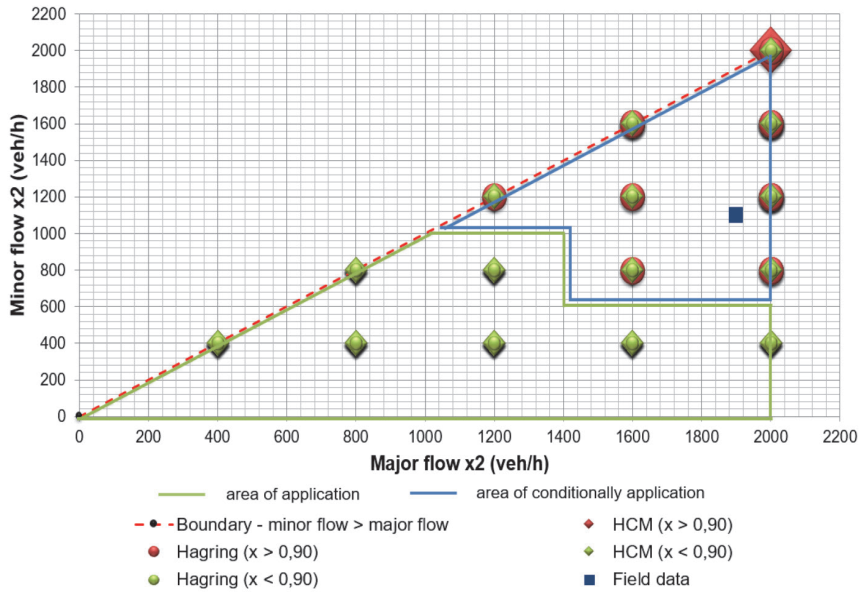


**Figure 8** Applicability of two-lane roundabout based on both methodology

Based on presented figures, several conclusions can be drawn:

- HCM methodology allows the application of two-lane roundabouts in almost all traffic scenarios, because only small part of the diagram, where both flows are 2000 veh/h, is conditionally applicable.
- Hagring method is more conservative compare to the HCM methodology and leads to a smaller overall capacity in several scenarios. Conditionally application area starts at 600-800 veh/h for major flows and 600-1000 veh/h for minor flows.
- In both methodologies, there is no unapplicable area which means that at least one traffic scenario did not reach an upper limit of degree of saturation.

Compare to the diagrams in HCM 2016, it is clear that results from this study fully cover the proposed applicability area. However, looking only HCM methodology application of two-lane roundabouts is possible regardless of traffic distribution pattern or traffic volume. Calculation based on Hagring method is more strict than the HCM method, which leads to smaller capacity values and application area. The main reason for this is the usage of four different sets of gap-acceptance parameters in order to describe driver behaviour better.
Overall, two-lane roundabouts can be applied unconditionally for major flows up to 1400 veh/h and minor flows up to 1000 veh/h, and for major flows up to 2000 veh/h and minor flows up to 600 veh/h. For the same major flows values and higher values of minor flows (upt to 2000 veh/h) two-lane roundabouts can be applied with some restrictions due to traffic distributions. In all scenarios with a clear unequal traffic distribution, regardless of the type of dominant movement, two-lane roundabouts have limited application for simultaneously high values of both major and minor flows.
In addition to theoretical scenarios, capacity was calculated for one existing two-lane roundabout. Based on obtained diagrams and existing traffic volumes on this roundabout, it was to be expected that it would be the conditionally right solution. Results of the capacity analysis showed that HCM 2010 provides a satisfied degree of saturation for all approaches. At the same time, according to Hagring methodology, not all movements have a degree of saturation below 0,90. This is consistent with the final diagrams presented of Figure 8.

## 4 Conclusion

Roundabouts are a widely accepted solution dealing with the different traffic problems. Their capacity is still one of the key element for their introduction in urban areas. Capacity calculation method and applicability of two-lane roundabouts in a particular situation are two connected problems.

Most of the existing researches suggest that fully gap-acceptance method is more suitable for this type of intersections. At the same time, a single value of future capacity is not sufficient to decode on building two-lane roundabouts. It is necessary to examine different traffic volumes and different traffic distribution patterns to make a full capacity image of one intersection. In this paper, we tried to solve that problem and to overcome the shortcomings of existing manuals, with a set of theoretical traffic distributions.

The results of the capacity analysis showed that the traffic distribution from scenario 6 gives the most unfavourable results according to both methods. In scenario 6, the main WB-EB direction is predominantly loaded, while from the minor approaches, 20 % of vehicles turn left. The results showed that a relatively small number of left-turning vehicles is sufficient to affect the quality of traffic of the entire roundabout significantly. Using the HCM method in all other scenarios, the degree of saturation was less than 0,90 and even for a very high volume of over 1000 veh/h in both directions. The most favourable scenario is 7 in which the degree of saturation is a maximum of 0,60 regardless of traffic volume, which is a consequence of a specific distribution of movement dominated only by right turns that do not conflict with other flows. Compared to the HCM method, the Hagring method shows significantly lower results in terms of capacity. Again, scenario 6 is the most unfavourable and 7 the best, however, oversaturated conditions also occur in all other scenarios for loads higher than 1000 veh/h on the major approach and 400 veh/h on the minor approach.

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