# Two-lane roundabouts

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## Abstract

To complete the Swiss standard "Efficiency, Traffic Quality and Capacity of Roundabouts" (SN 640 024a), in this research the entry capacity of two-lane roundabouts is analysed. For this evaluation the regression method and the time gap method are used. A focus is also placed on the traffic safety of this roundabout type.

## Keywords

Two-lane roundabout – Entry capacity – regression method – time gap method – traffic safety – accident rate

# 1. Initial situation

In the last few years roundabouts has become more common in Switzerland because of the traffic safety at a high level of capacity. But the capacity of a one-lane roundabout is limited and therefore now also multi-lane roundabouts are built.

The VSS standard “Efficiency, Traffic Quality and Capacity of Roundabouts” (SN 640 024a) contains the dimensioning correlations for one-lane roundabouts (Type 1/1) and for roundabouts with a two-lane entry and one extra-wide circulatory lane (Type 2/1+). For roundabouts with a two-lane entry and two circulatory lanes (Type 2/2) there is no dimensioning correlation in the Swiss standard. The main objective of this research is to complete the standard “Efficiency, Traffic Quality and Capacity of Roundabouts” (SN 640 024a) and provide the corresponding basic principles.

Furthermore there is an analysis of the traffic safety at two-lane roundabouts. The aim of this analysis is to provide a base for a comparison of the traffic safety of different types of roundabouts.

# 2. State of knowledge

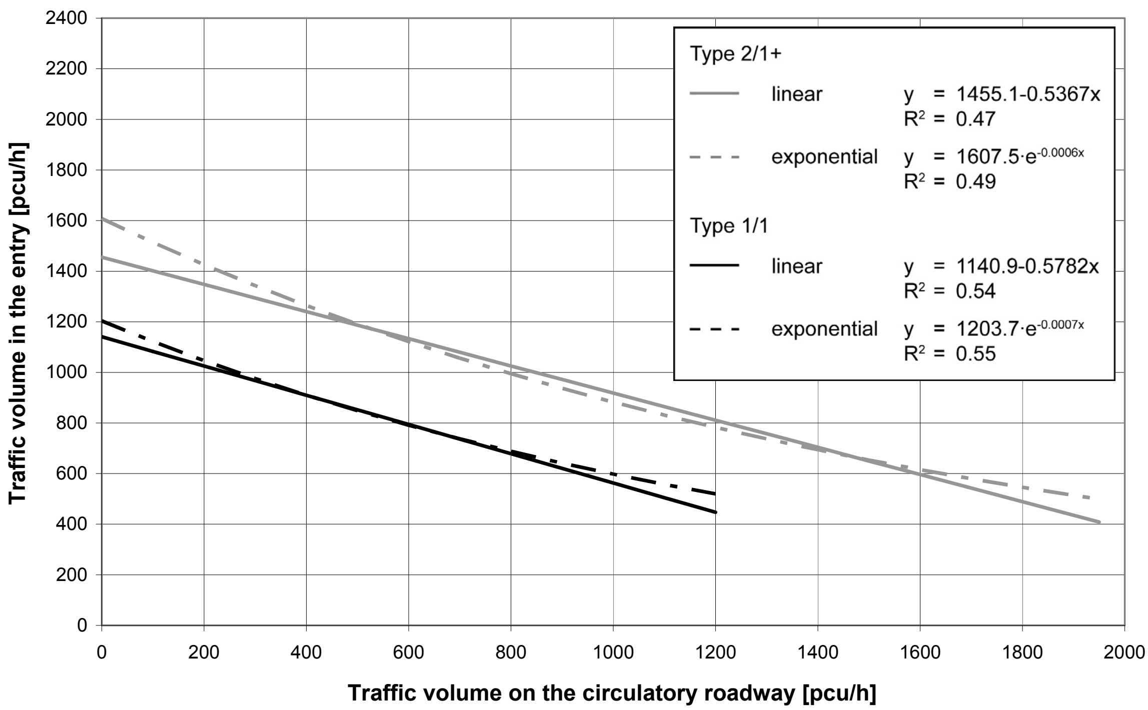
There are some studies about the capacity of roundabouts, but in Switzerland only research project about one-lane roundabouts had been realized. In Germany exist also e few studies about multi-lane roundabouts but with very differing results.

## 2.1 Switzerland

In the Swiss study "Capacity of Roundabouts in Saturated Conditions" (Lindenmann, 2004) a dimensioning correlation for one-lane roundabouts (Type 1/1) was developed. Also the capacity of roundabouts with a two-lane entry together with a single-lane extra wide circulatory roadway (Type 2/1+), a special type of roundabouts in Switzerland, was analysed. Based on the findings of this study the Swiss Standard was revised (SN 640 024a).

Figure 1 shows the entry capacity related to circulating flow by linear and exponential expression at roundabouts of Types 1/1 and 2/1+. The second entry lane provides an increase of the entry capacity about 200 to 300 pcu/h.

Figure 1 Entry capacity at roundabouts of Types 1/1 and 2/1+ (Lindenmann, 2004)



## 2.2 Germany

The formula for calculating the entry capacity of a roundabout in the German Highway capacity manual (HBS, 2001) bases on the critical gap and the follow up times. Furthermore the formula includes the number of entry lanes and also the number of circulatory lanes.

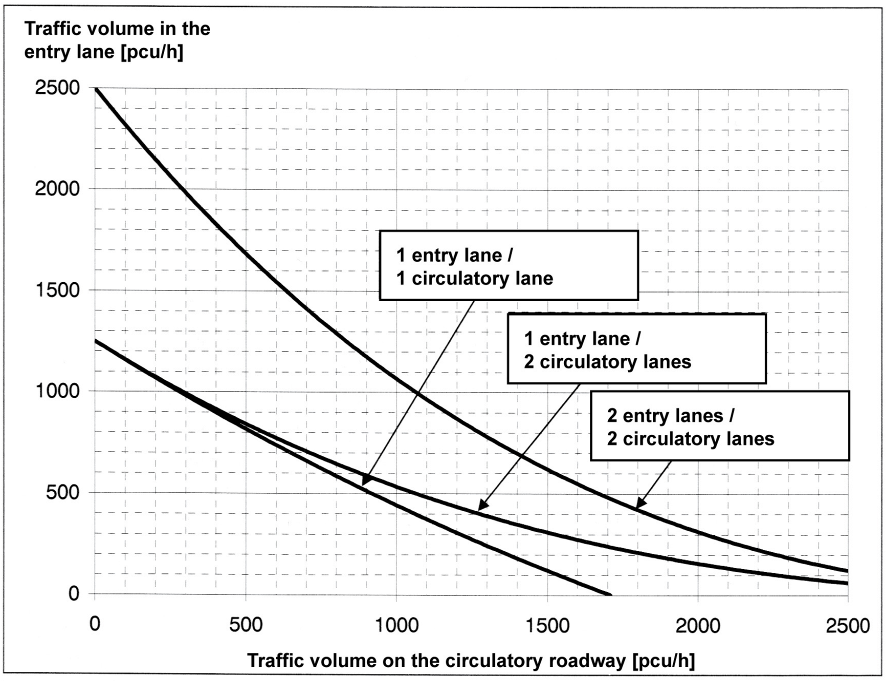
$$G = 3600 \cdot \left(1 - \frac{t_m \cdot q_c}{n_c \cdot 3600}\right)^{n_c} \cdot \frac{n_e}{t_f} \cdot e^{-\frac{q_c}{3600} \cdot \left(t_c - \frac{t_f}{2} - t_m\right)} \quad (1)$$

With $G$ = basic entry capacity [pcu/h]
$q_c$ = traffic volume on the circulatory roadway [pcu/h]
$n_c$ = number of circulatory lanes [-]
$n_e$ = number of entry lanes [-]
$t_c$ = critical gap [s]
$t_f$ = follow-up time [s]
$t_m$ = minimal time gap on the circulatory roadway [s]

with $t_c$ = 4.1 s, $t_f$ = 2.9 s, $t_m$ = 2.1 s

This capacity formula can be use for the most types of roundabouts. The Figure 2 shows the differences between the entry capacity of roundabouts of Types 1/1, 1/2 and 2/2.

Figure 2 Entry capacity at roundabouts of Types 1/1, 1/2 and 2/2 (HBS, 2001)



With the formula of the German Highway capacity manual (HBS, 2001) the entry capacity at a two-lane roundabout is much higher than at a one-lane roundabout. But it is assumed that in reality the influence of the second entry lane isn’t that high because both lanes are rarely used equally.

Brilon and Bäumer (Brilon, 2004-2) suggested a modified capacity formula for roundabouts with two entry lanes whit a smaller influence of the second entry lane than in the HBS.

$$G = 3600 \cdot \frac{n_e}{t_f} \cdot e^{-\frac{q_c}{3600} \cdot \left(t_c - \frac{t_f}{2}\right)} \qquad (2)$$

$n_e = 1.14$ 2 entry lanes

With $G$ = basic entry capacity [pcu/h]
$q_c$ = traffic volume on the circulatory roadway [pcu/h]
$t_c$ = critical gap [s]
$t_f$ = follow-up time [s]

with $t_c = 4.1$ s, $t_f = 2.5$ s

# 3. Data Collection

15 two-lane roundabouts in Switzerland with high traffic volume and different geometric characteristics had been selected for the research project. The data collection at each roundabout was carried out during the evening peak by a video camera. This videos form the base for the analysis of the traffic volumes and time gaps.

## 3.1 Traffic volumes

To analyse the entry capacity, each video was monitored and with the help of a computer program each vehicle in the entry and on the circulatory lane was registered with a timestamp. Furthermore for each vehicle in the entry the vehicle type and the entry lane (left or right) were recorded. Afterwards the saturated intervals of 30 seconds were searched with the following criteria:

- At the beginning of the interval, at least two vehicles wait one after other, either on the right or the left entry lane.

- During the interval, there is no longer time gap between two following vehicles in the entry than 4 seconds.

For the saturated intervals the traffic volume in the entry and the traffic volume on the circulatory lane were evaluated. For further use, the 30-second volumes were converted to hourly values according to the vehicle types.

Totally 1412 intervals of 30 seconds fulfilled the criterion of saturation. The data pairs (traffic volume in entry / traffic volume on circulatory lane) of these intervals formed the basis for the regression analysis.

## 3.2 Gaps

The videos were also monitored to evaluate the gaps in the circulating traffic flow accepted and rejected by the incoming vehicles. Each vehicle in the entry lane and on the circulatory lane was registered with a timestamp. This made it possible to calculate the accepted gap times and also the rejected gap times for each incoming vehicle. For further analysis only the vehicles which rejected in minimum one gap were observed. With this database, the critical gap and the follow-up times for each entry could be evaluated.

Totally 2013 gap times of 16 entries could be analyzed.

## 3.3 Traffic Safety

To analyse the traffic safety, the accident occurrence at 14 of the selected roundabouts were evaluated. For this evaluation the statistics of the accidents with information about accident severity, number of injuries and accident type for at least 3, usually for 5 years were available. For some roundabouts additionally accident report forms with a description of the accident could be used.

# 4. Method of analysis

## 4.1 Entry capacity

In the study two different methods to develop the dimensioning correlation for entry capacity were used:

- regression method
- time gap method

The Swiss standard is based on the regression method, the German Highway capacity manual (HBS, 2001) uses the time gap method.

### 4.1.1 Regression method

The data pairs of the saturated intervals formed the basis for the regression analysis. For each observed entry the relationship between entry capacity and circulating flow was investigated. In each case, linear and exponential regressions were tested.

To provide a dimensioning correlation the saturated intervals of all entries were analyzed together. Again linear and exponential regressions were tested and compared. Furthermore different groups of roundabouts were formed to test possible effects of the following geometric or characteristic properties:

- Diameter of roundabout
- Existence of signposts and direction-indicating pavement markings
- Distribution of traffic volume on the left and right entry lane

### 4.1.2 Time gap method

The maximum likelihood method described by Troutbeck (Troutbeck, 1992) was applied to determine the critical gap for each roundabout. As mathematical function for the statistic distribution of the time gaps a logarithmic normal distribution was used.

$$L = \sum_{i=1}^{n} \ln\left[F(a_i) - F(r_i)\right] \tag{3}$$

With $a_i$ = gap accepted by the *i*th driver
$r_i$ = largest gap rejected by the *i*th driver
F( ) = distribution of the critical gap;

$$F(x,\mu,\sigma) = \frac{1}{2} + \frac{1}{2}\mathrm{erf}\left[\frac{\ln(x)-\mu}{\sigma\sqrt{2}}\right] \tag{4}$$

$$\mu = e^{\mu+\sigma^2/2} \tag{5}$$

$$\mathrm{erf}(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}dt \tag{6}$$

$\mu$ = expected critical gap [s]

The distribution function F (Formula 4) includes the parameters $\mu$ and $\sigma$, for which the following equations must be fulfilled. The parameters were determined with an iterative solving of the equation set.

$$\frac{\delta L}{\delta\mu} = 0 \quad \text{and} \quad \frac{\delta L}{\delta\sigma} = 0$$

The follow-up time of each roundabout was determined with the arithmetic mean of the gap times, which has been used for a subsequent entry in the roundabout.

The relationship of the volumes in the entry and on the circulatory lane was calculated with different capacity formulas (for example Siegloch).

## 4.2 Traffic Safety

To analyse the traffic safety, the number of accidents per year and injuries/casualties per year were calculated for each roundabout. Afterwards the parameters of the roundabouts were compared. For some roundabouts the accident report forms were available and therefore the accident types and places could also be evaluated.

Besides absolute accident numbers also the accident rates of the roundabouts were analysed. The accident rate is calculated with the following formula.

$$U_R = \frac{U \cdot 10^6}{\frac{1}{2} \cdot \sum_{i=1}^{n} ADT_i \cdot 365 \cdot T} \tag{7}$$

With $U$ = number of accidents

$\frac{1}{2} \cdot \sum_{i=1}^{n} DTV_i$ = Average daily traffic in the roundabout [veh/d]

$T$ = observation period [years]

# 5. Results

## 5.1 Entry Capacity – Regression method

13 roundabouts and totally 16 entries were qualified for use in the regression analysis (Table 1). First the observed entry capacity was related to the circulating flow was for each entry. Then the saturated intervals of all entries were analyzed together. Furthermore different groups of roundabouts were formed to test possible effects of the geometric or characteristic properties.

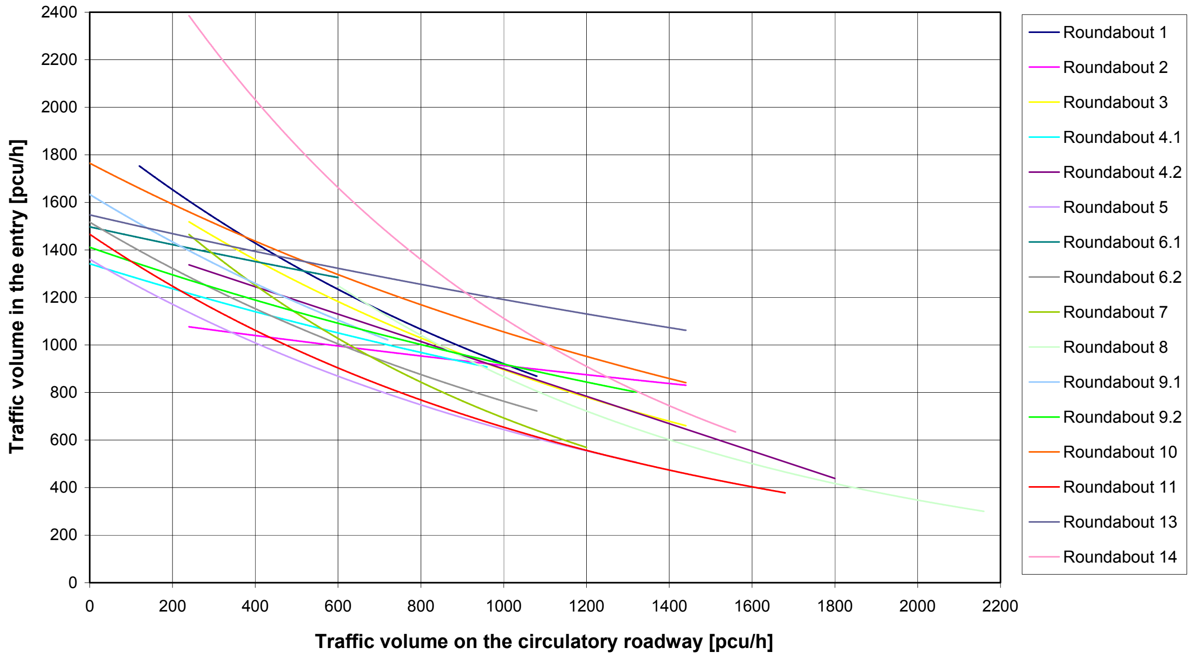
Table 1 Characteristics of the analysed entries

| No. | Location | Roundabout | Entry | Diameter [m] | Width of lanes [m] Circle | Width of lanes [m] Entry | Marks or signs |
|---|---|---|---|---|---|---|---|
| 1 | Pratteln | Frenkend.str. | Frenkend.str. Rtg. Liestal | 50 | 11.5 | 2 x 3.5 | Yes |
| 2 | Avry-sur-Matran | Avry-sur-Matran | Route de Fribourg | 35 | 8.0 | 2 x 3.75 | Yes |
| 3 | Avry-sur-Matran | Avry-Centre | Route de Matran | 40 | 11.0 | 2 x 3.5 | No |
| 4.1 | Matran | Bois des Morts | R. de Neyruz (Arm 3) | 34 | 9.0 | 2 x 3.75 | Yes |
| 4.2 | Matran | Bois des Morts | R. de la Pâla | 34 | 9.0 | 2 x 3.75 | Yes |
| 5 | Murten | Löwenberg | Rtg. A1 | 40 | 9.0 | 2 x 3.0 | Yes |
| 6.1 | Granges-Paccot | Lavapesson | R. de Morat Rtg. A12 | 36 | 9.0 | 2 x 3.5 | Yes |
| 6.2 | Granges-Paccot | Lavapesson | R. de Morat Rtg. Frib. | 36 | 9.0 | 2 x 3.0 | Yes |
| 7 | Granges-Paccot | Chenevière | Rtg. Cormagens | 42 | 12.0 | n.s.. | Yes |
| 8 | Kriens | Schlund | Anschluss A2 Rtg. Nord | 60 | 10.7 | 4.0 / 4.5 | Yes |
| 9.1 | Sursee | Glockenstrasse | Surentalstr. Rtg. Zentr. | 38 | 8.6 | 2 x 3.5 | Yes |
| 9.2 | Sursee | Glockenstrasse | Surentalstr. Rtg. AB | 38 | 8.6 | 2 x 3.5 | Yes |
| 10 | Sursee | Schlottermilch | Schlottermilch | 34 | 9.0 | 2 x 3.0 | No |
| 11 | Au | Adlerkreuzung | Zollstrasse | 34 | 9.5 | 6.5 | Yes |
| 13 | Lugano | Povro | Via Bioggio Rtg. Lugano | 40 | 9.5 | 2 x 4.0 | No |
| 14 | Vevey | Genevrier | Route du Rio Grédon | 40 | 10.0 | 10.0 | No |

### 5.1.1 Evaluation of each entry

With the data pairs of traffic volume in the entry and traffic volume on the circulatory roadway linear and exponential regression models were tested for each roundabout separately. The comparison shows that the differences between the both models were very small. Over the entire sample, it results a small advantage for the exponential model. Figure 3 shows the exponential regression curve of each entry.

Figure 3 Entry capacity (exponential regression) of each entry

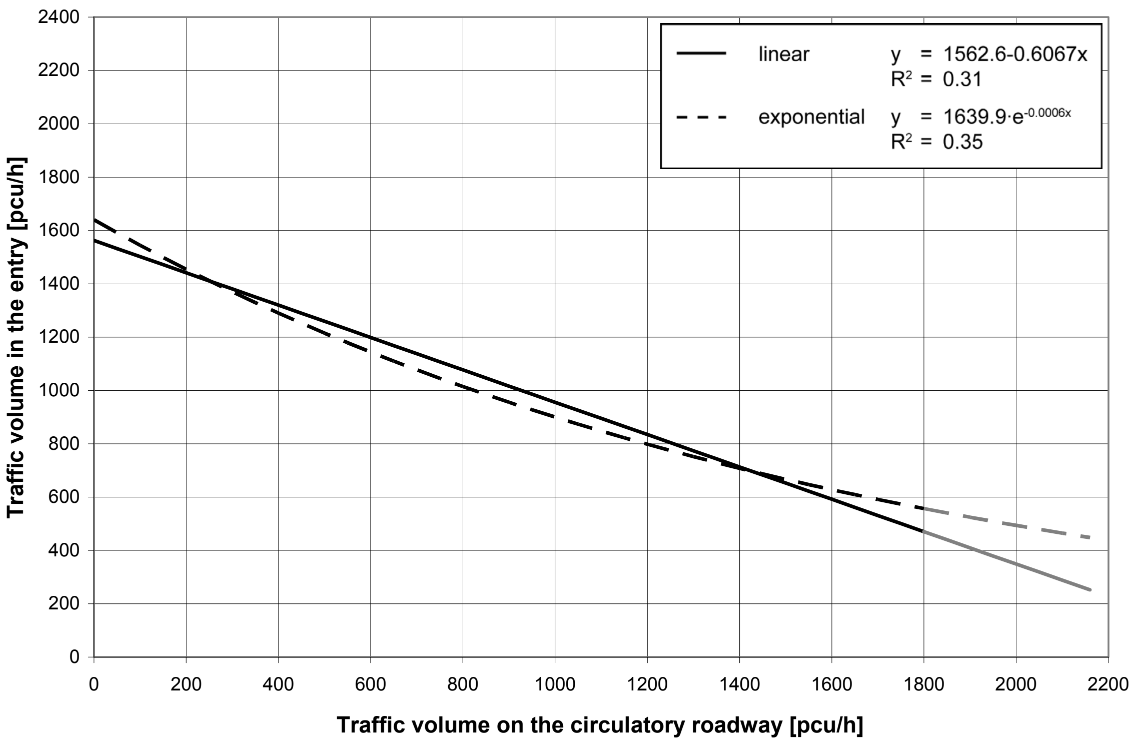



The regression curves of the observed entries, apart from roundabout 14, exhibit a similar form. The difference of the highest and the lowest entry capacity is approximately 400 pcu/h. In low and medium volumes on the circulatory roadway (up to 800 pcu/h) the entry capacity of roundabout 14 is considerably higher than the capacities of the other roundabouts. A possible explanation for this high entry capacity of roundabout 14 is the equal distribution of the traffic volume of both entry lanes in combination with a very high traffic flow in the entry. Therefore during a large part of the time there is a queue in both entry lanes. In case of low traffic volumes on the circulatory roadway the vehicles can drive easily parallel in the roundabout.

### 5.1.2 Evaluation of all entries

With the data pairs of all roundabouts (1412 intervals) the relationship between the entry capacity and the traffic volume on the circulatory roadway was evaluated. Linear and exponential regression models were tested and compared (Figure 4).

Figure 4 Entry capacity (regression method)




The comparison of the two regression models (Figure 4) indicates a high level of congruence. In medium traffic volumes the difference is about 100 pcu/h, in very heavy traffic volumes the difference is about 200 pcu/h. The regression coefficient of the exponential model ($R^2 = 0.35$) is little better than the one of the linear model ($R^2 = 0.31$). Therefore and for reasons of comparability the exponential model was chosen for further use.

The regression curves are illustrated up to 2150 pcu/h. But in the area of high traffic volume on the circulatory roadway there are only few observed intervals. Therefore these curves should only be used to dimension an entry of a roundabout with traffic volume on the circulatory roadway up to 1800 pcu/h.

The curve based on the exponential regression model gives a maximal entry capacity of a two-lane roundabout about 1600 pcu/h. When there are 1000 pcu/h on the circulatory roadway the entry capacity is about 950 pcu/h.

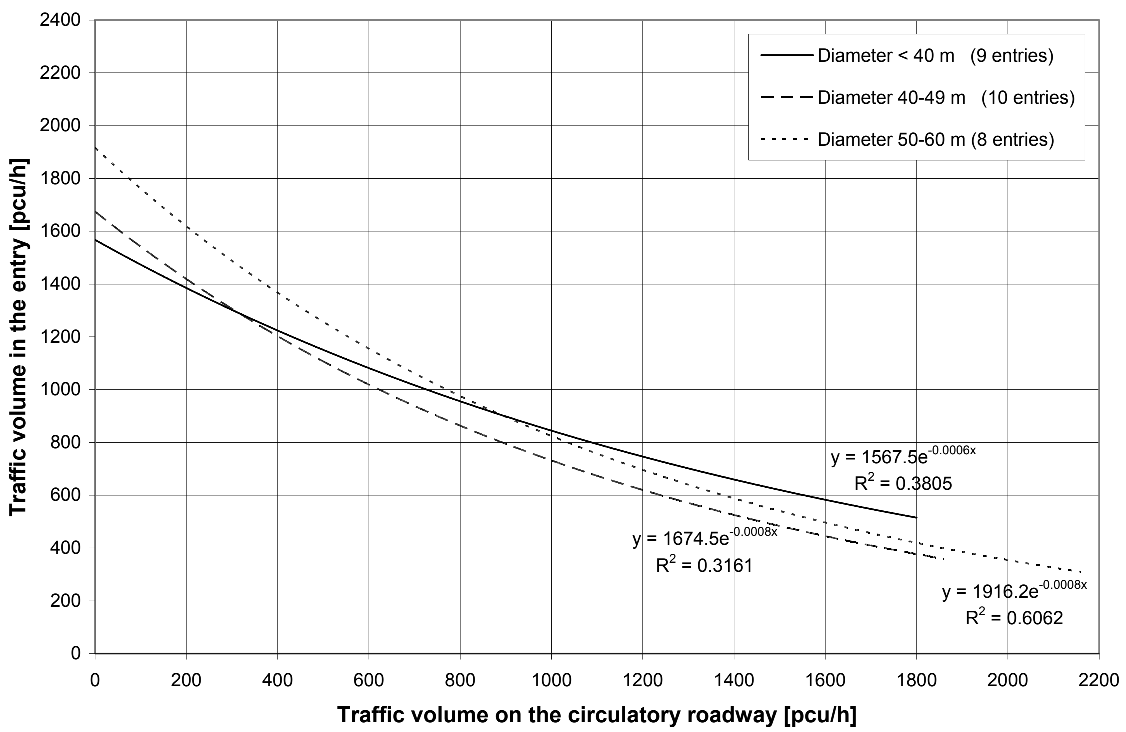
### 5.1.3 Influence of geometric or characteristic properties

#### *Diameter*

The range of diameter of two-lane roundabouts in Switzerland is very small. Only two of the 14 observed roundabouts have a diameter greater than 42 m. In order to be able to make a statement about the influence of the diameter on the entry capacity, additional data from Germany was used. The data pairs of 11 entries of roundabouts with diameter between 45 and 60 m of a similar research project in Germany were available.

With this database (16 entries in Switzerland and 11 entries in Germany) the influence of the diameter on the entry capacity was evaluated. Therefore the roundabouts were divided into three groups. The first group includes the roundabouts with a diameter smaller than 40 m, the second group those with a diameter from 40 up to 49 m and the last group the roundabouts with a diameter from 50 up to 60 m (Figure 5).

Figure 5 Relationship between entry capacity and traffic volume on the circulatory roadway depending on the diameter




In case of low traffic volumes on the circulatory roadway the largest entry capacity results, as expected, for the roundabouts with large diameter. But in heavy traffic volumes on the circulatory roadway the entry capacity of small roundabouts (diameter < 40 m) is higher than the capacity of large roundabouts.

This unexpected result can be explained with the speed of the vehicles on the circulatory roadway. It's expected that the speed in a large roundabout is higher than in a small one. With a higher speed level on the circulatory roadway the drivers in the entry need a longer time gap to enter the roundabout. In the case of high traffic volumes on the circulatory roadway thus longer waiting times in the entry develop and the entry capacity becomes lower.

### *Signposts and markings*

Signposts and direction-indicating pavement markings should optimise the traffic flow through a roundabout. The drivers should have a better overview and they should be able to change the lanes while approaching the roundabout. To check this assumption the roundabouts were divided into two groups depending on the existence signposts and direction-indicating pavement markings and linear and exponential regression models were compared (Figure 6).

Figure 6 Relationship between entry capacity and traffic volume on the circulatory roadway depending on the existence of signposts and direction-indicating pavement markings

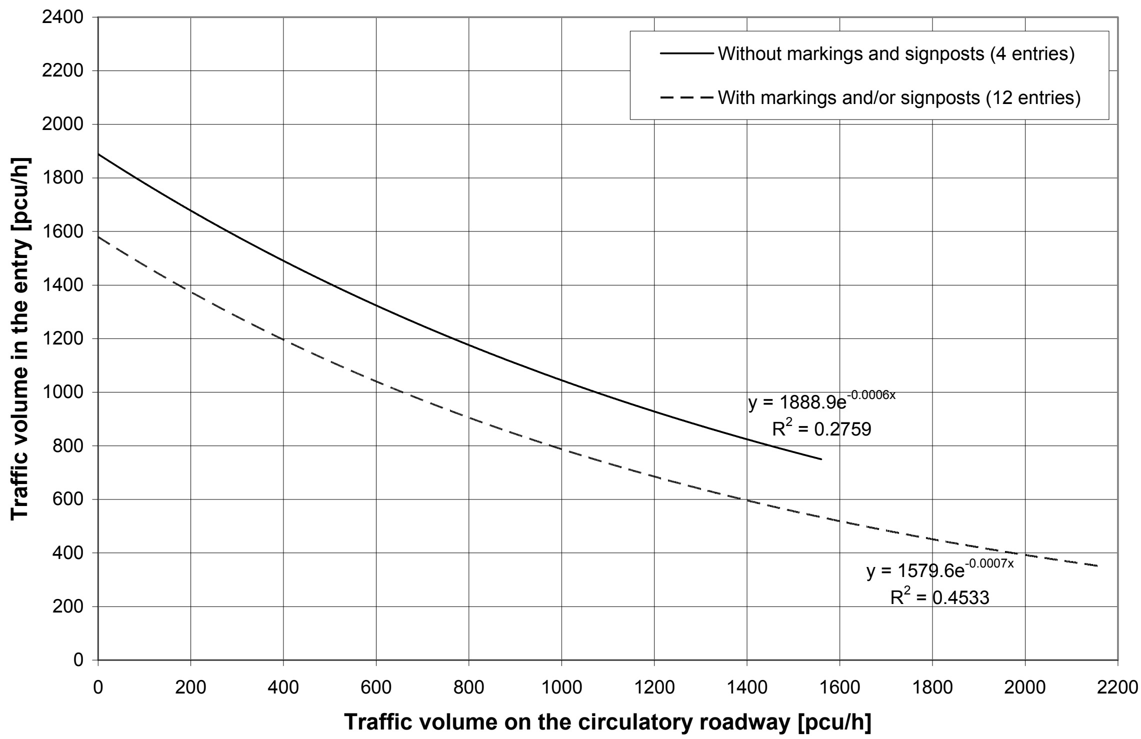



Figure 6 shows the unexpected result of the analysis of the influence of signposts and direction-indicating pavement markings on the entry capacity. Compared to scenarios with signposts or markings, it results the higher entry capacity for scenarios without signposts and markings. The differences are with 200 to 300 pcu/h considerable.

A more detailed analysis of the group of the roundabouts without signs and markings shows that at these roundabouts the traffic volume in the entry is almost equally distributed on both entry lanes also without this additional equipment (Table 2).

Table 2 Comparison of the distribution of traffic volume in the entries

| Signs and/or markings | Proportion of traffic volume on the less used entry lane |
|---|---|
| With signs and/or markings | 0.31 |
| Without signs and/or markings | 0.47 |

With the available data basis a conclusion about the appropriate use of direction signs and direction-indicating pavement markings is not possible.

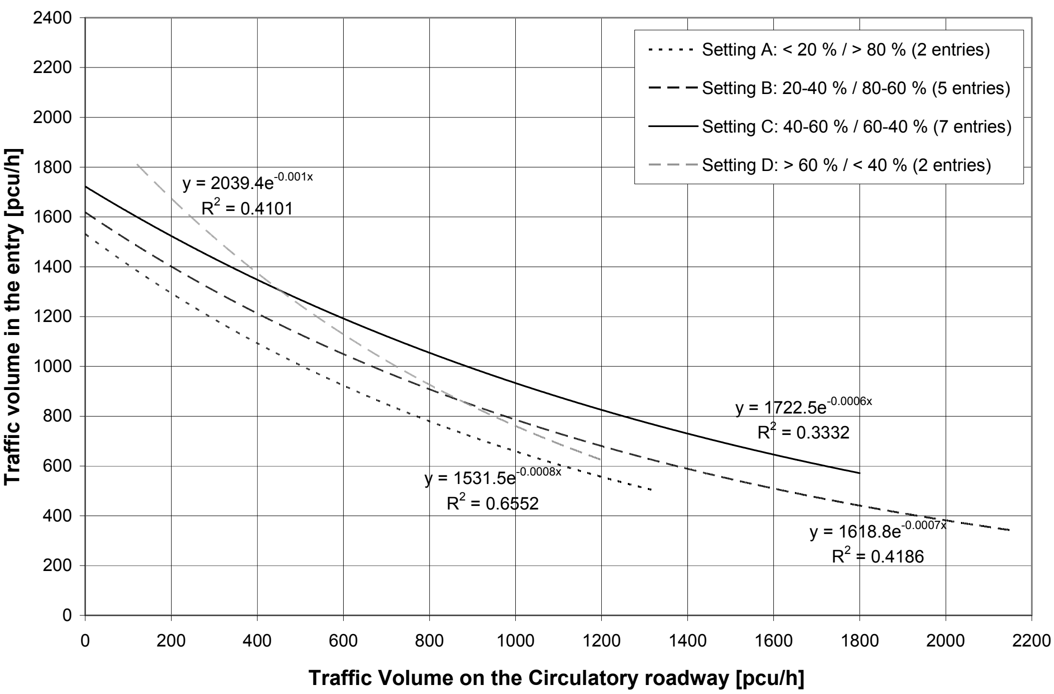
### *Distribution of traffic volume in the left and the right entry lane*

The distribution of the traffic volumes in each entry is available from the analysis of the videos for the regression method. For the evaluation of the influence of this distribution on the entry capacity the roundabouts are diveded into four groups (Table 3).

Table 3 Distribution of the traffic volume in the entry lanes

| | Left entry lane | Right entry lane |
|---|---|---|
| Setting A | < 20 % | > 80 % |
| Setting B | 20 % – 40% | 60 % – 80% |
| Setting C | 40 % – 60% | 40 % – 60% |
| Setting D | > 60 % | < 40 % |

Figure 7 Relationship between entry capacity and traffic volume on the circulatory roadway depending on the distribution of traffic volume in the left and the right entry lanes




The comparison of the entry capacity of the four groups of different distributions of the traffic volume in the entry (Figure 7) shows that the highest entry capacity results, as expected, with setting C. When there is a equal distribution of the traffic volume in the entry lanes, more vehicles can use the existing time gaps in the traffic flow on the circulatory roadway. This positive influence outweighs the negative influence of more conflict potential which develops when two vehicles have to filter in the traffic flow at the same time.

In case of low traffic volumes on the circulatory roadway results the highest entry capacity for the group with a high traffic volume in the left entry lane (setting D). But it has to be noted that there is small data set (2 entries) for this setting.

Compared to an uneven distribution (settings B and D, an equal distribution of the traffic volume in both entry lanes (setting C) is leading to a higher entry capacity. The average difference is around 150 pcu/h. Low traffic volume in the left entry lane (setting A) is leading to the lowest entry capacity.

### 5.1.4 Time gap method

Critical gaps and follow-up times were evaluated from the videos for each roundabout as described (4.1.2). Table 4 shows the evaluated gaps for the 16 entries which are used for the analysis of the entry capacity with the time gap method.

Table 4 Critical gap and follow-up time of each entry

| No. | Location | Roundabout | Entry | Critical gap $t_c$ [s] | Follow-up time $t_f$ [s] |
|---|---|---|---|---|---|
| 1 | Pratteln | Frenkend.str. | Frenkend.str. Rtg. Liestal | 4.16 | 2.46 |
| 2 | Avry-sur-Matran | Avry-sur-Matran | Route de Fribourg | 3.86 | 2.50 |
| 3 | Avry-sur-Matran | Avry-Centre | Route de Matran | 4.31 | 2.27 |
| 4.1 | Matran | Bois des Morts | R. de Neyruz (Arm 3) | 4.33 | 2.47 |
| 4.2 | Matran | Bois des Morts | R. de la Pâla | 3.68 | 2.61 |
| 5 | Murten | Löwenberg | Rtg. A1 | 3.58 | 2.63 |
| 6.1 | Granges-Paccot | Lavapesson | R. de Morat Rtg. A12 | - * | 2.51 |
| 6.2 | Granges-Paccot | Lavapesson | R. de Morat Rtg. Frib. | 4.03 | 2.41 |
| 7 | Granges-Paccot | Chenevière | Rtg. Cormagens | 4.23 | 2.53 |
| 8 | Kriens | Schlund | Anschluss A2 Rtg. Nord | 3.22 | 2.36 |
| 9.1 | Sursee | Glockenstrasse | Surentalstr. Rtg. Zentr. | 3.93 | 2.61 |
| 9.2 | Sursee | Glockenstrasse | Surentalstr. Rtg. AB | 4.29 | 2.59 |
| 10 | Sursee | Schlottermilch | Schlottermilch | 3.88 | 2.59 |
| 11 | Au | Adlerkreuzung | Zollstrasse | 3.94 | 2.76 |
| 13 | Lugano | Povro | Via Bioggio Rtg. Lugano | 3.49 | 2.58 |
| 14 | Vevey | Genevrier | Route du Rio Grédon | 4.28 | 2.34 |
| Mean | | | | 3.92 | 2.52 |

* $t_g$ couldn't be calculated

The differences between the critical gaps are quite large: the lowest $t_c$ is 3.22 s, the highest 4.33 s. The variation of the follow-up times at the different entries is with 0.5 s smaller.

The mean value of the critical gaps is slightly lower than the suggested value of 4.1 s in the HBS (HBS 2001). The mean value of the follow-up times is with 2.5 s considerably lower than the value of 2.9 s in the HBS. But with a value of 2.5 s nearly the same follow-up time resulted in the research project of Brilon and Bäumer (Brilon 2004).

In the context of the present research work the entry capacity were determined with the following three formulas of Siegloch (Siegloch 1973), Wu (Wu 1997, HBS 2001) and Brilon (Brilon 2004-2).

Siegloch:

$$G = \frac{3600}{t_f} \cdot e^{-\frac{q_c}{3600} \cdot \left(t_c - \frac{t_f}{2}\right)} \tag{8}$$

With G = basic entry capacity [pcu/h]
$q_c$ = traffic volume on the circulatory roadway [pcu/h]
$t_c$ = critical gap [s]
$t_f$ = follow-up time [s]

Wu / HBS:

$$G = 3600 \cdot \left(1 - \frac{t_m \cdot q_c}{n_c \cdot 3600}\right)^{n_c} \cdot \frac{n_e}{t_f} \cdot e^{-\frac{q_c}{3600} \cdot \left(t_c - \frac{t_f}{2} - t_m\right)} \tag{9}$$

With G = basic entry capacity [pcu/h]
$q_c$ = traffic volume on the circulatory roadway [pcu/h]
$n_c$ = number of circulatory lanes [-]
$n_e$ = number of entry lanes [-]
$t_c$ = critical gap [s]
$t_f$ = follow-up time [s]
$t_m$ = minimal time gap on the circulatory roadway [s]

with $t_m$ = 2.1 s

Brilon:

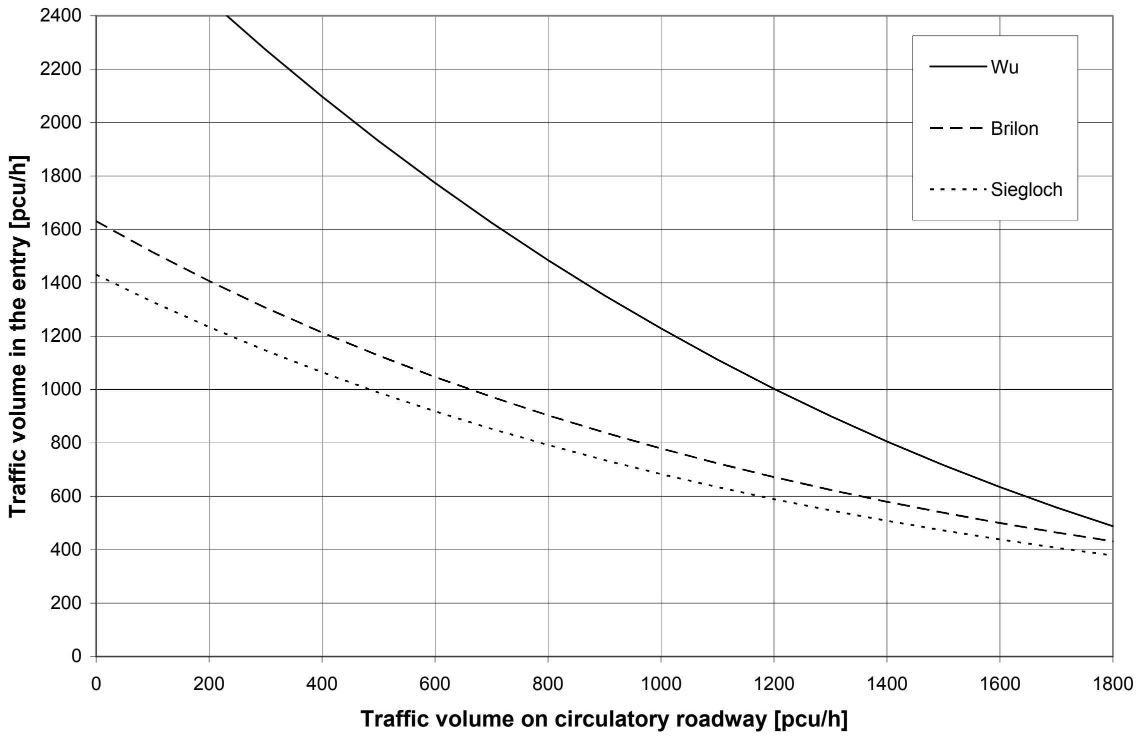
$$G = 3600 \cdot \frac{n_e}{t_f} \cdot e^{-\frac{q_c}{3600} \cdot \left(t_c - \frac{t_f}{2}\right)} \tag{10}$$

$n_e$ = 1.14 2 entry lanes

With G = basic entry capacity [pcu/h]
$q_c$ = traffic volume on the circulatory roadway [pcu/h]
$t_c$ = critical gap [s]
$t_f$ = follow-up time [s]

Figure 8 shows the entry capacity based on the three formulas and the mean of the evaluated critical gaps and follow-up times (Table 4).

Figure 8 Entry capacity (time gap method)




The highest entry capacity results with the formula of Wu. The effect of the doubling because of the second entry lane is stronger than the effect of the reduction because of a possible traffic jam on the circulatory roadway. The other two curves are similar because the formula of Brilon bases on the formula of Siegloch. The formula of Brilon contains an additional factor for the effect of the second lane. But this factor is with a value of 1.14 clearly smaller than in the formula of Wu.

### 5.1.5 Comparison of entry capacity using regression method and time gap method

The results of the analysis of the entry capacity with both methods can be compared. For this comparison the exponential curve of the regression method is used (Figure 9).

Figure 9 Entry capacity: comparison of regression method and time gap method

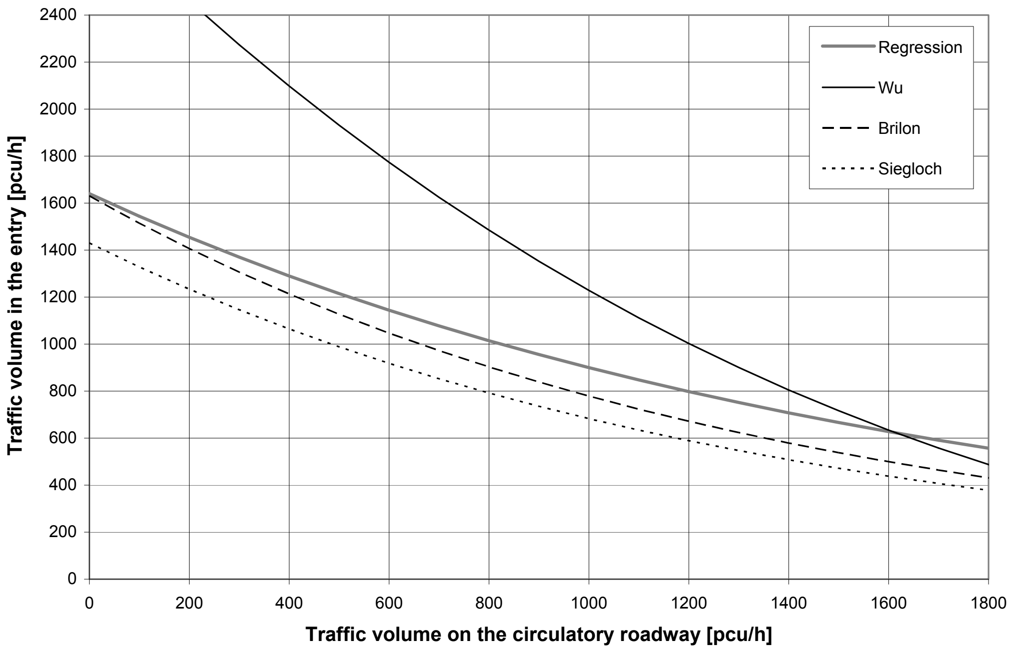



Figure 9 shows that the curve based on the regression method is similar to the curve based on the formula of Brilon which uses the observed time gaps of this study. In heavy traffic volumes there is a difference of 100 to 150 pcu/h between the two curves. The curve with the Siegloch formula has the same shape like the regression curve with a constant difference of 200 pcu/h.

The curve based on the formula of Wu has, as expected, a totally different shape compared to the regression curve. The differences in low traffic volumes are greater than 700 pcu/h. In heavy traffic volumes the differences become smaller and when with a traffic volume of 1600 pcu/h on the circulatory roadway the same entry capacity is calculated.

These comparisons show that the differences between the regression method and the time gap method are small if a suitable formula is used for the time gap method. The formula of Brilon, based on the latest research results, seems to be a good approximation. Furthermore the comparisons show that the curve based on the regression method can be used as dimensioning correlation.

### 5.1.6 Comparison with other types of roundabout

The resulted ratio of traffic volume on the circulatory roadway to the traffic volume in the entry for two-lane roundabouts is compared to the results of the study of one-lane roundabout and roundabouts with a two-lane entry and one-lane circulatory roadway (Lindenmann, 2004). For this comparison the exponential curves of both studies are used (Figure 10).

Figure 10 Comparison of the entry capacity of different roundabout types

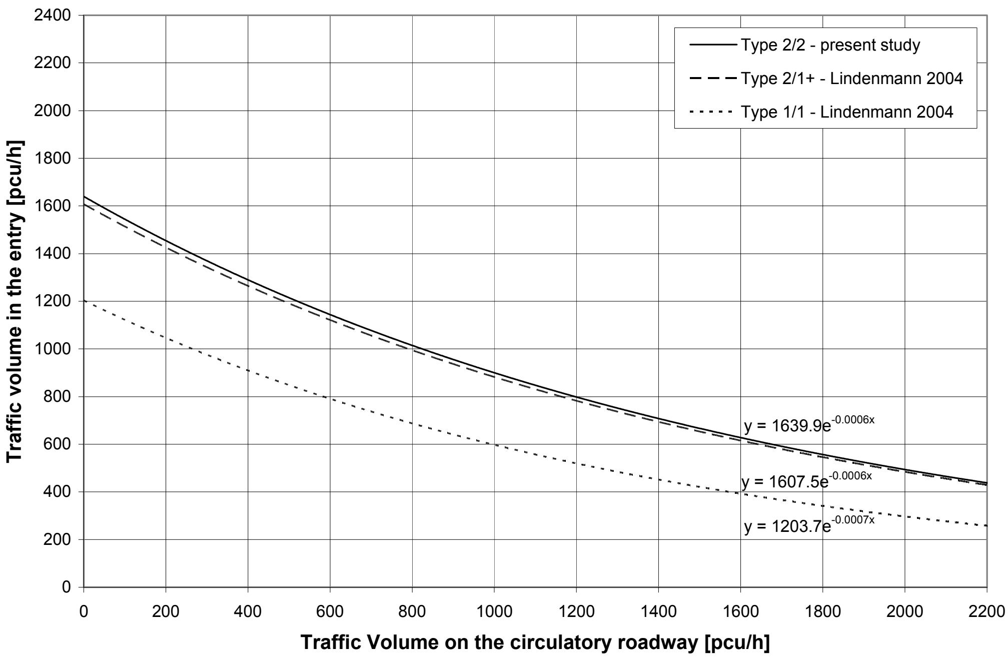



Figure 10 shows the unexpected result of the comparison of the entry capacity of different roundabout types. There is nearly no difference between the curves of Type 2/1+ and Type 2/2. That means that the existence of the marking of the tow lanes on the circulatory roadway has no influence on the capacity. Compared to the curve of one-lane roundabouts, the entry capacity of a two-lane roundabout is 200 to 400 pcu/h higher. In low traffic volumes the differences between the two curves is higher than in heavy traffic volumes.

## 5.2 Traffic Safety

### 5.2.1 Absolute parameters of traffic safety

To analyse the traffic safety, 254 accidents in 14 observed roundabouts could be took as basis. Table 5 shows for each roundabout the average number of accidents and injuries/casualties per year during the observation period.

Table 5 Number of accidents and injuries/casualties at each roundabout

| | No. of roundabout | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | Mean |
| Accidents per year | 5.3 | 2.2 | 1.6 | 3.6 | 1.0 | 1.2 | 2.2 | 6.2 | 3.0 | 2.4 | 7.0 | 3.8 | 4.3 | 9.2 | 3.79 |
| Injuries/casualties per year | 3.3 | 1.4 | 0.2 | 0.6 | 0.4 | 0.2 | 0.7 | 0.9 | 0.5 | 0.6 | 1.4 | n.s. | n.s. | 1.2 | 0.95 |

The average number of accidents over all observed roundabouts is 3.79 accidents per year. There are major differences between the roundabouts: the lowest value is 1.0 accident per year (roundabout 5), the highest one is 9.2 accidents per year (roundabout 15). The numbers of injuries and casualties vary from 0.2 to 3.3 injuries/casualties per year. The mean value is 0.95 injuries/casualties per year. But it must be pointed out that no casualty was registered during the observation period.

To filter out special accidents at two-lane roundabouts, an evaluation of the distribution of accidents in the roundabouts was made. Besides the number of accidents and injuries/casualties, Table 6 shows also the accident severity. The accident severity is the quotient of the number of injuries/casualties and the number of accidents.

Table 6 Distribution of the accidents in the roundabout (without roundabout 13 and 14)

| | Accidents | | Injuries/casualties | | Accident severity |
|---|---|---|---|---|---|
| Entry area | 90 | (44.8 %) | 28 | (58.3 %) | 31.1 % |
| Circulatory roadway | 80 | (40.3 %) | 9 | (18.8 %) | 11.1 % |
| Exit area | 29 | (14.4 %) | 11 | (22.9 %) | 37.9 % |
| No specified | 1 | (0.5 %) | 0 | (0.0 %) | 0.0 % |
| Total | 201 | (100 %) | 48 | (100 %) | 23.9 % |

Most accidents in a roundabout happen in the entry area and on the circulatory roadway. The number of accidents in the exit area is with 14.4 % relatively small. But the exit area has the highest accident severity. That means that in this area only few but serious accidents happen. A contrary result shows the evaluation of the accidents for the circulatory roadway. There are a lot of accidents but only few injuries and therefore the accident severity is low.

Table 7 shows the distribution of the accident types where the accidents are distributed in five groups.

Table 7 Distribution of the accidents types (without roundabout 13 and 14)

| | Accidents | | Injuries/casualties | | Accident severity |
|---|---|---|---|---|---|
| Self accident | 37 | (18.4 %) | 9 | (18.8 %) | 24.3 % |
| Rear-end accident | 20 | (10.0 %) | 15 | (31.3 %) | 75.0 % |
| Lane changing accident | 73 | (36.3 %) | 5 | (10.4 %) | 6.9 % |
| Turning accident (exit) | 2 | (1.0 %) | 0 | (0.0 %) | 0.0 % |
| Turning accident (entry) | 63 | (31.3 %) | 17 | (35.4 %) | 26.2 % |
| Other accidents | 6 | (3.0 %) | 2 | (4.1 %) | 28.6 % |
| Total | 201 | (100 %) | 48 | (100 %) | 23.9 % |

Most accidents happen during lane changing (36.3 %) or entering the roundabout (31.3 %). Self accidents (18.4 %) and rear-end accidents (10. %) are also common accidents in roundabouts. The statistic of injuries/casualties and the accident severity shows that rear-end accidents are often fatal accidents. The accident severity of this accident type is with 75.0 % clearly higher than of the other accident types. On the contrary, lane changing accidents happen very often but the accident severity is very low.

To find possible differences between the traffic safety in one-lane and two-lane entries and exits, the distribution of the accidents in one-lane and two-lane entries and exits was examined (Table 8).

Table 8 Distribution of accidents in one-lane and two-lane entries / exits

| | Number of entries / exits | ϕ accidents/year |
|---|---|---|
| One-lane entry | 18 | 0.36 |
| Two-lane entry | 39 | 0.67 |
| One-lane exit | 47 | 0.10 |
| Two-lane exit | 9 | 0.72 |

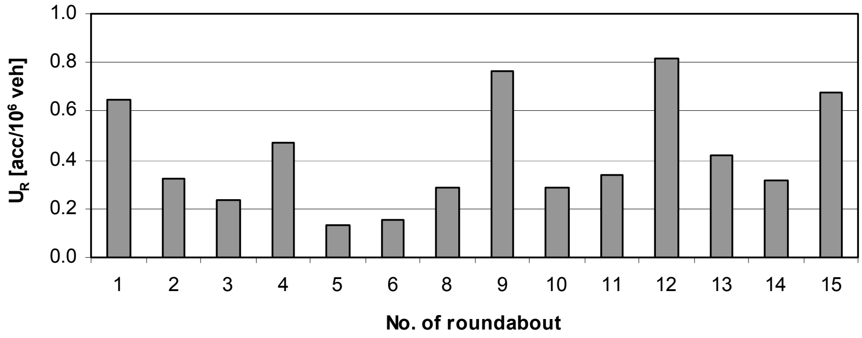
The distribution of the accidents in one-lane and two-lane entries shows a clearly higher number of accidents in two-lane entries. But the traffic safety in the entries with two lanes is higher than in the entries with one lane. With the assumption that the traffic volume in the entries with two lanes is about twice as much as in the entries with one lane, the accident numbers are almost on the same level.

The number of accidents per year in a two-lane exit is seven times larger than in a one-lane exit. This difference can not be explained with the traffic volumes. Therefore the analysis of the accidents shows that two-lane exits are a traffic safety problem and should be avoided. This finding confirms the German guideline permits two-lane exits only under special conditions.

### 5.2.2 Relative parameters of traffic safety

To compare the accident occurrence in the roundabouts, also the total traffic volume in the roundabout should be included in the evaluation. Therefore the accident rate, which refers the accidents to the traffic volume (AADT) in the roundabout, was calculated (Figure 11).

Figure 11 Accident rate of each roundabout

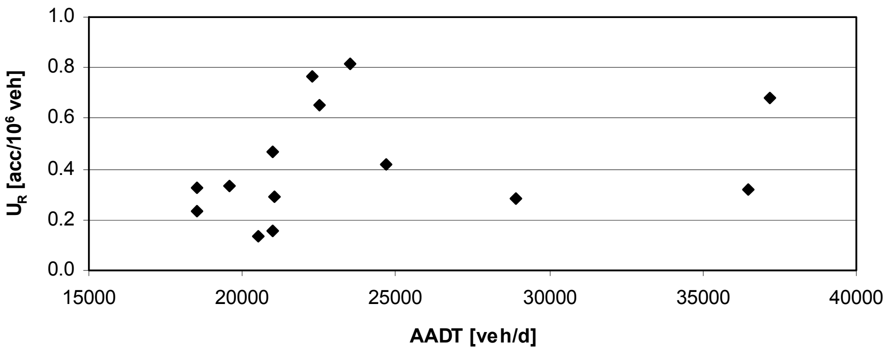



The average accident rate is 0.42 acc/$10^6$ veh. In spite of including the traffic volumes, the range of the results of the individual roundabouts is with 0.7 acc/$10^6$ veh still large. Figure 11 shows that the accident rates of four roundabouts are clearly higher than the average accident rate.

The average accident rate is low in comparison with the result of a study of Brilon in Germany [Brilon, 2004-1] where the accident rate for two-lane roundabouts was 0.99 acc/$10^6$ veh. One reason for this difference is the higher speed level in the roundabouts in Germany.

Generally is assumed that the accident occurrence rises disproportionally with the traffic volume in the roundabout because the conflict potential rises ever more, if the roundabout is saturated. Therefore the relationship between the accident rate and the traffic volume was evaluated. Figure 12 shows that this assumption could not be supported. In case of the heavy traffic volumes the speed level is lower than in low traffic volumes. That could be one reason for the relatively low accident rate in the two roundabouts with very heavy traffic volumes.

Figure 12 Relationship between the accident rate and the traffic volume



### 5.2.3 Comparison with other types of roundabouts

Generally the accident occurrence at two-lane roundabout seems to be higher than at one-lane roundabouts. But two-lane roundabouts are built where the traffic volumes are high and therefore the accident rate has to be regarded.

A comparison with the traffic safety of other roundabout types is difficult because there are only few specifications in other studies. Accident rates in Switzerland are known for roundabouts with 3, 4 or 5 arms [Matthews, 2009], but there is no differentiation of the number of lanes. It can be assumed that most of the observed roundabouts are one-lane roundabouts. Therefore a comparison with the results of Matthews was made (Table 9).

Table 9 Distribution of accidents in one-lane and two-lane entries / exits

| | Reference | Accident rate [acc/$10^6$ veh] |
|---|---|---|
| Two-lane roundabout | Present study | 0.42 |
| Roundabout with 3 branches | [Matthews, 2009] | 0.27 |
| Roundabout with 4 branches | [Matthews, 2009] | 0.53 |
| Roundabout with 5 branches | [Matthews, 2009] | 0.69 |

The comparison with the accident rate of roundabouts from Matthews shows that the accident rates from one-lane and two-lane roundabouts are on the same level.

# 6. Conclusion

The evaluation of the entry capacity of two-lane roundabouts lead to following findings:

- The entry capacity of two-lane roundabouts is significantly higher than that of one-lane roundabouts. The differences are between 200 to 400 pcu/h.

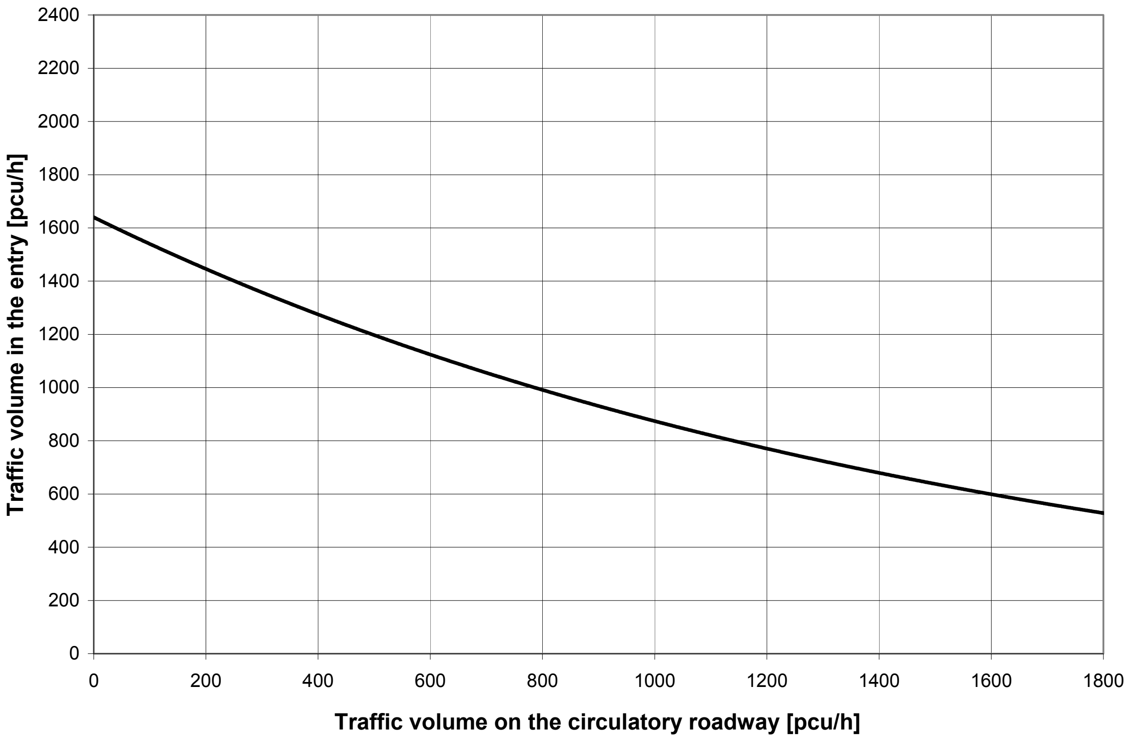
- The entry capacities of two-lane roundabouts and roundabouts with a two-lane entry and one extra wide circulatory lane are almost at the same level.

- The influence of the distribution of the traffic volume in both entry lanes has to be included in the dimensioning. With the results of the evaluation of the influence of signposts it is assumed that it's difficult to control this distribution.

- Other geometric or characteristic properties like the diameter affect the entry capacity less. The influence of this parameter has to be check for each individual case.

Figure 13 shows the dimensioning correlation which forms the basis to complete the Swiss standard SN 640 024a.

Figure 13 Suggested Dimensioning Correlation for two-lane roundabouts



This dimensioning correlation for two-lane roundabouts bases on the following formula.

$$G = 1639.9 \cdot e^{-0.0006 \cdot q_c} \tag{11}$$

With $G$ = basic entry capacity [pcu/h]
$q_c$ = traffic volume on the circulatory roadway [pcu/h]

The evaluation of the traffic safety shows that the safety level of two-lane roundabouts is comparable with the safety level of one-lane roundabouts. Therefore a two-lane roundabout is a good alternative to other intersection types when there is the necessity of a high entry capacity.

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