# A CAPACITY ANALYSIS PROCEDURE FOR UNSIGNALIZED INTERSECTIONS IN SWITZERLAND

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## ABSTRACT

Unsignalized intersections are widely used in Switzerland, especially where traffic volumes are relatively low. This paper presents a capacity analysis procedure for unsignalized intersections in Switzerland, including yield- or stop-controlled intersections and roundabouts. A method of estimating queues and delays that accounts for traffic flow variations at unsignalized intersections is also proposed. Roundabout Operations Analysis Program (ROAP), a software program for analyzing roundabout capacity, queues, and delays is presented, and some aspects of development of unsignalized intersection design are briefly discussed.

## INTRODUCTION

The common space shared by several conflicting traffic streams at intersections is a major source of traffic accidents. To prevent traffic accidents, conflicting traffic streams are separated either in space or in time. Because grade-separated intersections (which remove the shared space) require more space and higher construction costs, conflicting traffic streams are more often separated in time, by traffic signs or rules governing priority (unsignalized intersections) or by traffic signals (signalized intersections). Some intersections combine signals with traffic signs or rules governing priority.

Unsignalized intersections are widely used in Switzerland, especially where traffic volumes are relatively low. The following are types of unsignalized intersections:

- Intersections controlled by right-side priority rules
- Stop-controlled intersections
- Yield-controlled intersections
- Roundabouts

According to Swiss traffic law, where there are neither traffic signals nor traffic signs, the right-side priority rule applies (i.e., a driver approaching the intersection should give way to vehicles arriving from his right side). Normally, only the intersections of two minor roads are governed by this rule alone; intersections where a major and a minor road intersect usually have stop and/or yield signs. Roundabouts may also be used at intersections where two major roads intersect.

The purpose of this paper is to present a method used in Switzerland for capacity analysis of unsignalized intersections and to discuss some aspects of unsignalized intersection design.

## CAPACITY ANALYSIS OF UNSIGNALIZED INTERSECTIONS

The objective of capacity analysis is to estimate available capacity and capacity used, the main performance indexes of intersection operation. The capacity ($C_e$, in vph) of an intersection entry or an intersection entry lane is defined as the maximum inflow of the entry or the lane concerned. The capacity used (in %) is the ratio of the traffic volume to the corresponding capacity.

For the capacity used function, traffic queues and delays must also be estimated. For example, if the capacity used of an entry or lane is 70-100%, a traffic queue may form. In this case, it is important to further estimate the delays, especially the queue length, to determine whether there is sufficient storage capacity for the queue. If the capacity used of an entry or lane is equal to or greater than 100% (oversaturation), a long queue will form. In such a case, measures to decrease capacity used and provide sufficient storage capacity, including design changes, must be detemined.

Because the right-side priority rule is applied only at intersections where traffic flow is very low (rural areas, residential areas, and especially in traffic calming zones), there is no capacity problem and no procedure for analyzing the capacity of this type of intersection. In the following subsections, only yield- or stop-controlled intersections and roundabouts are discussed.

## Yield- or Stop-Controlled Intersections

The capacity of traffic movement with priority at an intersection is independent of other traffic streams and amounts to 1,700-1,900 vehicles per hour per lane (vphpl), but the capacity of the movement without priority (i.e., controlled by a yield sign, stop sign, or traffic rules) depends on other movements at the intersection.

For each movement without priority, the capacity should be estimated. The procedure of estimating the capacity is described as follows [1]:

*Calculating Conflict Traffic Volume ($Q_c$, in vph) for a Non-Priority Movement*

For a given movement without priority, the total conflicting volume that has priority over this movement should be determined. The methods for calculating the total conflicting volume for different types of non-priority movements are as follows:

(A) Turning right onto a main road from a minor road (Figure 1A).

$$Q_c = 0.5\ Q_1 + Q_2$$

If there is a separate lane for $Q_1$, $Q_1$ is omitted. If there are several lanes for $Q_2$, only the traffic volume on the right-side lane is considered as $Q_2$.

(B) Turning left onto a main road from a minor road (Figure 1B).

$$Q_c = 0.5\ Q_1 + Q_2 + Q_3 + 0.5\ Q_4 + Q_5 + Q_6 + Q_7 + Q_8$$

If there is a separate lane for $Q_1$, $Q_1$ is omitted. If there is a separate lane for $Q_4$, $Q_4$ is omitted.

(C) Going ahead and crossing a main road from a minor road (Figure 1C).

$$Q_c = 0.5\ Q_1 + Q_2 + Q_3 + Q_4 + Q_5 + Q_6$$

If there is a separate lane for $Q_1$, $Q_1$ is omitted.

(D) Turning left onto a minor road from a main road (Figure 1D).

$$Q_c = Q_1 + Q_2$$

If there is a yield sign or a stop sign for $Q_1$, $Q_1$ is omitted.

*Determination of Critical Gap*

Critical gap values are listed in Table 1 according to type of conflict, type of traffic sign (yield or stop), and location of intersection (residential or rural area).

*Estimation of Capacity*

Using the critical gap value and the conflict traffic volume determined in the previous sections, the theoretical capacity ($C_e$) can be found as shown in Figure 2. The capacity used (%) is:

$$100 \times Q_d / C_e$$

The difference between the theoretical capacity and the real traffic volume ($Q_d$) is calculated as:

$$Q_{dif} = C_e - Q_d$$

Traffic disturbance at the entry or entry lane studied is considered large if $Q_{dif} \leq 100$ and small if $Q_{dif} > 200$.

## Offside-Priority Roundabouts

A roundabout is a special type of intersection where traffic moves counterclockwise around a center island. The offside-priority, or give-way-at-entry, rule is used at roundabouts—i.e., entering vehicles must give way to vehicles on the ring road. This practice has proved effective in Switzerland.

Offside-priority roundabouts have the following main advantages:

- There are few accidents because there are fewer conflict points.
- Accidents are relatively minor because all traffic moves in the same direction and the speed of entering vehicles is relatively low (because they must yield).
- Traffic regulation at the intersection is simpler (conflict flows are separated by the offside-priority rule).
- Operation cost is very low.
- Investment cost could be low.

In Switzerland, the number of roundabouts has increased exponentially from 20 to 700 in the last 16 years, and hundreds of new roundabouts are being planned. With the offside-priority rule, roundabouts may be small or compact, making them suitable for urban areas where the land available for intersections is quite limited. About 70% of the existing roundabouts and 67% of projected roundabouts are located in urban areas [2].

At roundabouts, entry streams must give way and have no priority. The method for estimating the entry capacity is described below [3, 4, 5].

Entry capacity ($C_e$) of a roundabout is defined as the maximum inflow at the entry concerned. $C_e$ depends on conflicting traffic volume ($Q_c$), including vehicles traveling across the entry ($Q_{cir}$), and on gaps left by vehicles leaving the roundabout at the exit on the same leg of the roundabout ($Q_s$).

The following formula for estimating the entry capacity ($C_e$, in vph) is based on a simulation study and field observations in Switzerland:

$$C_e = \kappa \times [1500 - (8/9) \times Q_c]$$

where

$$Q_c = \beta \times Q_{cir} + \alpha \times Q_s$$

and α is named as coefficient of disturbance. It is the parameter indicating the influence of leaving vehicles on entry flow. β is the parameter for converting the case of multi-lane circulating carriageways to that of single-lane case. κ is the parameter for converting the case of multi-lane entry to that of the single-lane case. α, β, and κ are determined according to roundabout geometry.

The value of a is determined as shown in Figure 3. Because U-turns are rare, vehicles leaving from the right leg of a three-leg roundabout have very little effect on entry flow. Only the exit flow from the left leg is taken as exit volume $Q_s$ when applying the formula. The circulating speed is assumed to be 20-25 kph. If the speed is higher than this value, more disturbance can result; and the value of a determined here should be adjusted accordingly (generally in the interval [α, α+0.1]). If the speed is lower, a should be adjusted in [α-0.1, α]; however, the adjusted value of α should not be less than zero.

The values of κ and β are determined as follows:

$\kappa = 1.0$ if $NL_e = 1$
$\kappa = 1.0\text{-}2.0$ if $NL_e = 2$
$\kappa = 1.0\text{-}3.0$ if $NL_e = 3$
$\beta = 1$ if $W_c < 8$ and $NL_c = 1$
$\beta = 0.9$ if $W_c \geq 8$ and $NL_c = 1$
$\beta = 0.7 - 0.9$ if $W_c > 8$ and $NL_c = 2$
$\beta = 0.5 - 0.7$ if $W_c > 12$ and $NL_c = 3$

where

$NL_e$ = the number of lanes in the entry

$NL_c$ = the number of lanes in the circulating carriageways

$W_c$ = the width of circulating carriageways (m)

The reserve entry capacity (in vph) is the difference between the entry capacity ($C_e$, vph) and the entry flow ($Q_d$, vph), i.e.,

$$C_e - Q_d$$

The capacity used at entry (in %) is determined by

$$100 \times (Q_d/k) / C_e$$

## Estimation of Queues and Delays

As mentioned above, traffic delays and especially queue length should be estimated if the capacity used is high. There are two methods of estimating the traffic queue length (L, in veh) and delays (d, in sec/veh). The first is used to estimate the mean queue and delays without taking account of traffic flow variations; the second is used to estimate variations in queue and delay, incorporating flow variations. Usually the second method is preferable.

*Formulae Without Taking Account of Flow Variations*

The formulae based on the queuing theory for calculating average queue length (L, in veh) and delays per arriving vehicle (d, in sec/veh) without taking account of flow variations are

$$L = \rho/(1-\rho) \qquad (\rho<1)$$
$$d = L \times 3600/Q_d$$

where

$\rho = Q_d/C_e$

$C_e$ = capacity

$Q_d$ = real traffic volume

Field observations indicate that the formulae give quite good predictions when $\rho < 0.8$, but not when $\rho > 0.8$.

*Formulae Incorporating Flow Variations*

Real-world traffic flows do not arrive uniformly, so the value of ρ varies with the time. The mean value of ρ may be relatively low during a 1-hour period, but at some point in this hour, the value of ρ can be high, even higher than 1 (e.g., the peak-hour period). This means that the formula that does not include flow variations cannot describe real-world situations (especially for the peak period), where queue length and delays vary with traffic flows. Based on Kimber's formulae [6], field observations, and simulations, the formulae that includes flow variations have been proposed as follows [4, 7]:

Average queue length:

$$L = 0.5 \times ((A^2+B)^{1/2}-A)$$

where

$$A = (1 - \rho) \times \lambda \times \mu \times t + (1 - \lambda \times L_0)$$
$$B = 4 \times \lambda \times [L_0 + (1/\zeta + \rho - 1) \times \mu \times t]$$
$$\rho = q/\mu$$

q = flow rate arriving at entries (veh/sec)

μ = the entry capacity (veh/sec)

t = the time interval (sec)

$L_0$ = queue at the beginning of time interval (veh)

The value of $\lambda$ and $\zeta$ are determined by

$\lambda = 1/\{1 + 0.2 \times \min[\rho, 1.5]\}$ if $r \geq 0.8$

$\lambda = 1$ if $r < 0.8$

$\zeta = 1 + \rho^3$ if $r \geq 0.8$

$\zeta = 1$ if $r < 0.8$

Average delay:

$d = 0.5 \times ((C^2 + E)^{1/2} - C)$

where

$C = \lambda \times [t \times \mu \times (1 - \rho)/(2 \times q) - L_0/q]$

$E = 2 \times \lambda \times t/(\zeta \times q)$

$\rho = q/\mu$

or simply calculate it from average queue length

$d = L/q$

*Flow Variation Predictions*

Applying the formulae mentioned in the previous section involves using traffic flow data in a sequence of short time intervals. However, only average peak hour flow data ($Q_{peak}$, in vph) are usually available in practice. Thus, a method to estimate traffic flow data for a sequence of short time intervals from 1-hour peak flow data should be developed using $Q_{peak}$ (vph) to find out $f(x_i)$, i=1, 2, ....., k, which satisfies

$f(x_1)+f(x_2)+......+f(x_k) = Q_{peak}$

and fits real-world traffic situations.

Based on analysis of real data in Switzerland and some assumptions, a method of predicting traffic peak shapes has been developed (for details, see section 5.6 of reference [4]).

The idea is to first determine a group of coefficients $u_i$, (i=1, 2, ....., n. n=60/t, t being the length of time interval used), which satisfies

$u_1 + u_2 + ...... + u_n = 1$

and the following conditions:

(a) $u_i$ arrives at its maximum value ($u_{max}$) at the middle sub-interval of the 1-hour interval, that is, $u_i = u_{max}$ at i = int (n/2) and i = int (n/2) + 1

(b) the curve of $u_i$ is symmetrical at about the centerline (line from the middle sub-interval of the 1-hour interval to the maximum value of $u_i$)

(c) $u_i$ increases uniformly to the maximum value from the first sub-interval to the middle sub-interval of the 1-hour interval

(d) $u_i$ reaches its minimum value ($u_{min}$) at the first sub-interval of the 1-hour interval, that is, $u_1 = u_{min}$

(e) $u_{min} \leq u_{max}$

Then

$f(x_i) = u_i \times Q_{peak}$ (i=1, 2, ....., n. n=60/t)

For the case t=5 minutes, $u_i$, (i= 1 , 2, . .... , n. n=60/t) is determined by

$u_6 = u_7 = u_{max}$

$u_1 = u_{12} = u_{min}$

$u_2 = u_{11} = (1/5)u_{max} + (4/5)u_{min}$

$u_3 = u_{10} = (2/5)u_{max} + (3/5)u_{min}$

$u_4 = u_9 = (3/5)u_{max} + (2/5)u_{min}$

$u_5 = u_8 = (4/5)u_{max} + (1/5)u_{min}$

$u_{min}$ and $u_{max}$ are determined from

$u_{min} = 1/[6 \times (1+\omega)]$

$u_{max} = \omega/[6 \times (1+\omega)]$

where $\omega = u_{max} / u_{min}$ is the ratio of maximum volume to minimum volume. The higher the value of $\omega$, the higher the degree of flow variation will be. If $\omega$=1, the flow arrives uniformly. Field-observed values of $\omega$ are listed in Table 2.

## ROAP: A ROUNDABOUT OPERATIONS ANALYSIS PROGRAM

Roundabout Operations Analysis Program (ROAP) is a software program developed and marketed in MacIntosh and Windows versions to provide recent research results and a useful tool for practicing engineers.

ROAP predicts capacities, queues, and delays at roundabouts. It can perform detailed analysis of queues and delays, taking into account flow variations during peak hours. ROAP can be used to test design alternatives for new roundabouts and modifications of existing ones. The roundabouts analyzed in the program can have up to six legs.

The input data, as shown in Figure 4, are:

- Diameter of roundabout
- Number of legs
- Width and lane number of ring road
- Lane number and distance Lba for each entry
- Intersection traffic volumes (OD, in vph)

The four parameters for calculating capacity, queues, and delays (α, β, κ, and ω) can be modified according to the user's judgment or the program can default to automatic calculation of the four parameters based on input data.

The results of the capacity estimation procedure (Figure 5) include:

- Entry capacity (vph)
- Reservation of entry capacity (vph)
- Entry capacity used (%)
- Entry capacity used at conflict point (%)
- Average queue length (veh)
- Average delay (sec/veh)

The main results from estimating the variation of queue and delay (Figure 6) are:

- Arriving flow shape (veh in 5-minute intervals)
- Variation of entry queue (veh in 5-minute intervals)
- Variation of entry delay (sec/veh in 5-minute intervals)

## DEVELOPMENT OF UNSIGNALIZED INTERSECTION DESIGN

Before performing capacity analysis, an intersection design should be proposed. In practice, various designs are proposed and by comparative study, including intersection capacity analysis, the best design for the intersection will be determined. Clearly, it is very important that good intersection designs should be proposed.

To develop an unsignalized intersection design, the following main factors should be taken into account:

- Constraints
- Traffic volumes
- Conflict area
- Number of conflict streams
- Total conflicting traffic volume
- Conflict angle/type
- Clearness of design
- Storage space for traffic queue (non-priority movements)
- Levels of priority

A good intersection design should first satisfy the constraints and have a limited conflict area, fewer conflict streams, minimized total conflicting traffic volume, and enough storage space for queueing, and also be easily understood by users. A good intersection design should indicate clearly who has priority and who should yield, and it should be easy to determine driver responsibility in case of accidents.

The following methods can be used to minimize conflict area:

- Traffic island
- Pavement markings

Methods to reduce the number of conflict streams are:

- One-way roads
- Pavement markings

Methods to reduce total conflict number are:

- Limitation of the arriving traffic
- Separate lanes for different movements

Methods to eliminate severe crossing conflict or severity of accidents are:

- Roundabout designs
- Prohibiting crossing movement
- Traffic calming to reduce approaching vehicle speed

Turning radii of vehicles using the intersection should also be taken into account in the design of an intersection, especially if buses or larger vehicles will use the intersection.

All-way stop-controlled intersections are not used in Switzerland and are not included in Swiss road legislation because it is impossible to determine driver responsibility in accidents at such intersections. The documented use of and experience with all-way stop-controlled intersections in other countries may be useful in introducing this type of intersection in Switzerland.

## SUMMARY

This paper presents a capacity analysis procedure for yield- and stop-controlled intersections and roundabouts in Switzerland. A method for estimating queues and delays at unsignalized intersections and a software program for analyzing roundabout capacity, queues, and delays in Switzerland are also presented. In addition, some aspects of the development of unsignalized intersection design are briefly discussed.

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Table 1. Critical Gap for a Non-Priority Entry Lane

| | Inside locality | | Outside locality | |
|---|---|---|---|---|
| | Yield sign | Stop sign | Yield sign | Stop sign |
| | 5" | 6" | 5.5" | 7" |
| | 3" | - | 4" | - |
| | 5" | - | 5.5" | - |
| | 6" | 7" | 7" | 8" |
| | 6.5" | 7.5" | 8" | 9" |

Table 2. Observed Values of "ω"

| ω(mean) | ω(50%) | ω(75%) | ω(90%) |
|---|---|---|---|
| 1.75 | 1.60 | 1.88 | 2.35 |

Figure 1. Estimation of Conflicting Volume for a Non-Priority Entry Lane

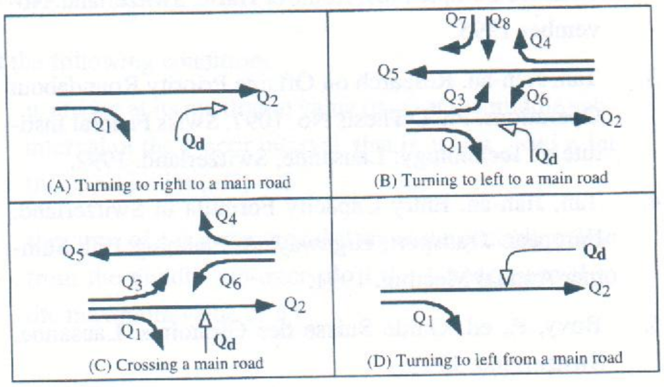


Figure 2. Estimation of Theoretical Capacity

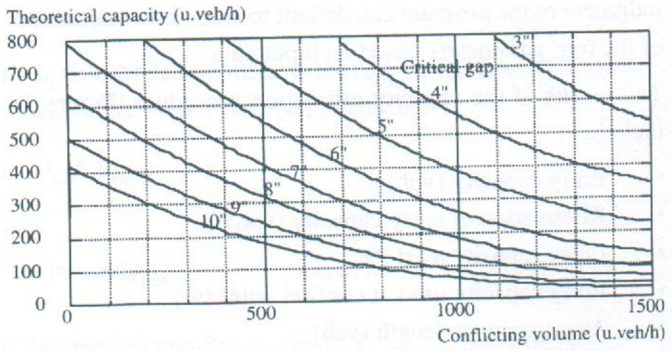


Figure 3. The Relationship Between Coefficient a and Lba

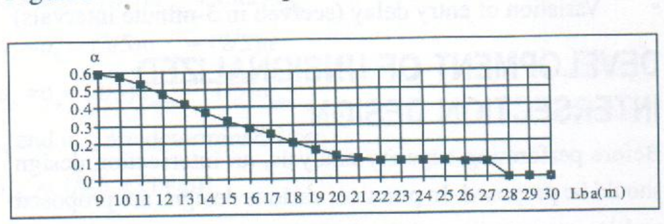


Figure 4. Data Input Screen

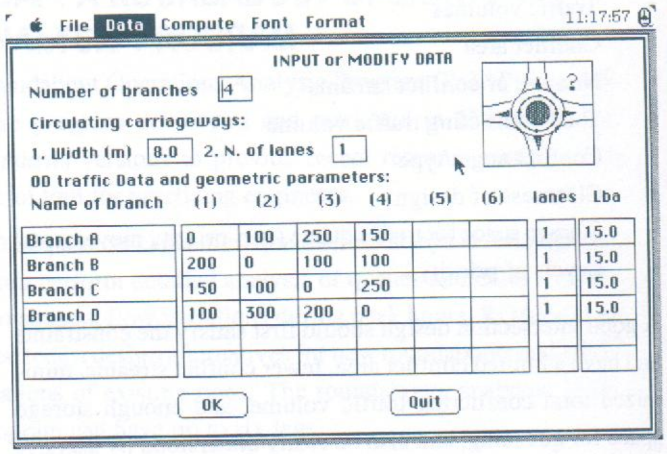

Figure 5. Results of Estimated Entry Capacity

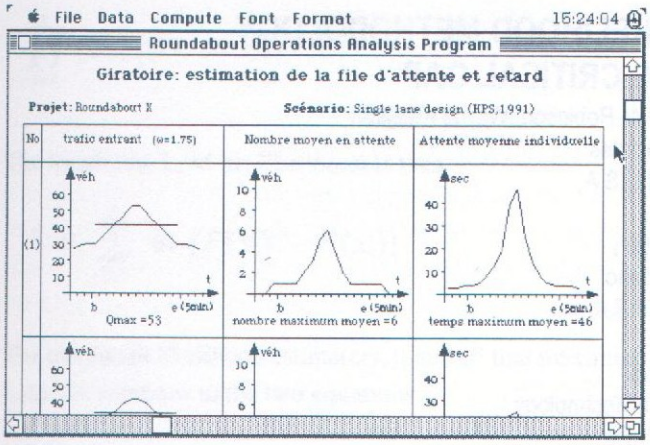


Figure 6. Results of Estimated Entry Queue and Delay