ROAD CAPACITIES

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INDEVELOPMENT

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1 INTRODUCTION

This document provides information about a traffic flow theory and simulation models and it provides information about capacities of road networks.

Capacity is usually defined as:

The maximum hourly rate at which persons or vehicles can reasonably be expected to traverse a point or uniform section of a lane or roadway during a given time period under prevailing roadway, traffic and control conditions.

2 MOTORWAYS

Road networks

Road networks are composed of intersections and links. If the links are long enough, the intersections will no longer have influence on the behaviour of the traffic on a link. The capacity of the road network is thus different near the intersection than on long links. This chapter will first discuss the capacities on the long links and subsequently the capacities of some types of intersections.

Traffic stream characteristics

The traffic stream has three main characteristics:

- Intensity
- Density
- And mean speed

Intensity

The intensity of a traffic flow is the number of vehicles passing a cross section of a road in a unit of time. The intensity is expressed with “q”.

Thus in formula: $q= n/T$ or

Intensity = number of vehicles/unit of time

Density

The density of a traffic flow (k) is the number of vehicles (m) present on a unit of road length (X) at a given moment.

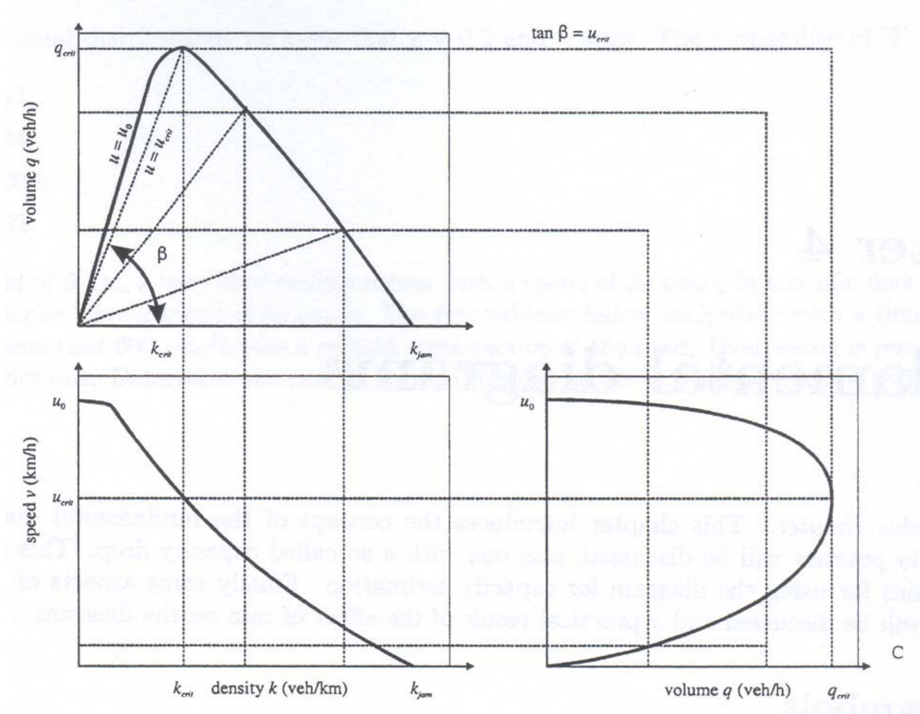
Thus in formula: $k= m/X$

If the traffic flow is in a stationary and homogeneous state, then the following relationship is valid: density multiplied with mean speed (u) equals the intensity.

In formula: $q=k*u$

Three fundamental diagrams

In traffic flow theory there are three fundamental diagrams:
Intensity-density $q=q(k)$
Speed-density $u=u(k)$
Speed-intensity $u=u(q)$

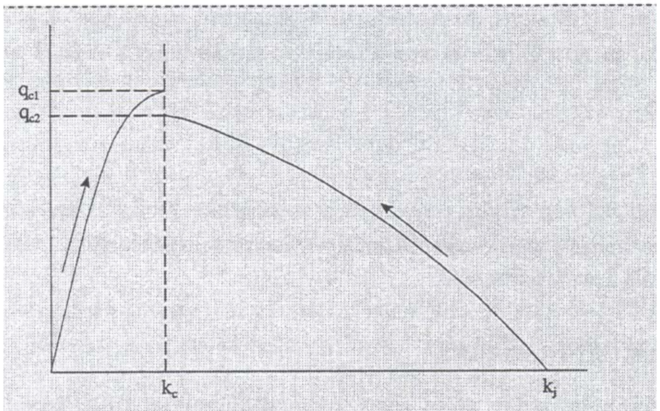


The relations in the diagrams tend to depend on characteristics of the road, drivers and their vehicles and conditions like lightning and weather.

It is therefore common that the exact relationship differ from country to country but also varies over time. First of all the composition of the traffic changes but also traffic behaviour is totally different. In western world people tend to drive faster and keep less distance between the bumpers of each other cars. On their highways they separated slow from fast moving traffic and roads are usually lighted. In many low and middle-income countries traffic behaves in a less disciplined manner and that affects the average speed of the vehicles.

Eddie

Eddie was the first researcher to indicate the possibility of a discontinuity in the diagram around the capacity point. It was observed that an increasing traffic stream that moves in free flow reaches a higher capacity than a diminishing traffic stream moving from a congested situation into a free flow situation.



intensity/density diagram with 2 maxima

More lanes

If a road is composed of different lanes, it is not correct to add the diagrams of the different lanes to compile a diagram for the whole road. In particular the distribution of the traffic over the different lanes have major complications. It appears that the upper mean speed of a multi-lane highway almost remain constant until the road get congested.

Overtaking vehicles

This phenomenon can be partly be explained due to changing lanes of overtaking vehicles and therefore changing intensities at the different lanes.

Dominant traffic rules

This process depends also partly on the traffic rules on multi-lane roads. Basically there are two systems.

1. Keep your lane
2. Fast lane

Keep your lane

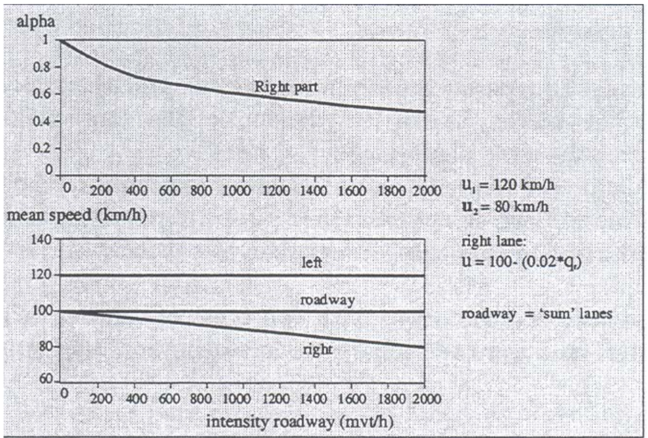
Keep your lane implies that traffic will stay in its lane until it wants to take over another vehicle. To take over the vehicle, it could either move to the left or right lane as it pleases.

Fast lane

Fast lane system means that vehicles in principle will use the outer lane, until it wants to take over. After having taken over the vehicles in the inner lanes, it moves back to the outer lane. Thus the inner lane is used for taking over only.

When the traffic intensity increases and reaches congestion, more and more vehicles will stay in the inner lanes, and traffic starts using the keep your lane system.

With increasing intensity, that starts and still is in free flow situation, it is noticeable that traffic in the outer lanes are slowing down, while traffic in the inner (fast) lanes keep their high speed. But because more and more traffic is using the inner lanes, the average speed of all traffic tends to remain constant.



To estimate the capacities of roads, it is necessary to take these aspects into account.

Maximum free flow

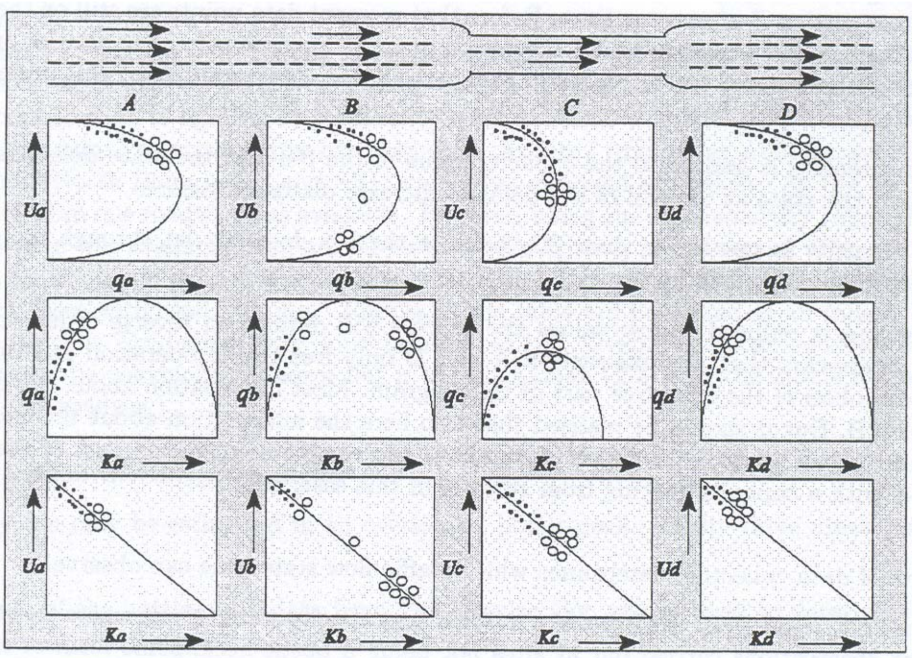
It is possible to calculate the maximum free flow capacity by fitting a model of the function q(k) to data. The capacity is the maximum of q(k).

Queue discharge

To estimate the queue discharge capacity, it is necessary to set-up three measuring stations in and near the overloaded bottlenecks.

1. Upstream of the bottleneck
2. Downstream of the bottleneck, the traffic should move freely, thus there is no congestion
3. At the bottleneck

At an overloaded bottleneck the intensities at the three stations are more or less the same. The station downstream is than used to measure the traffic flow, because it has the smoothest traffic flow.



2.1 CAPACITY AND LEVEL OF SERVICE ANALYSIS

Level of service

An important question is how much traffic the road can carry. Current studies present the relationships between the capacity of the road link/node and the resulting level-of-service offered to the user of the road.

LOS	Flow conditions	*v/c* limit	Service volume	Speed	Density
			(veh/h/lane)	(miles/h)	(veh/mile)
A	Free	0.35	700	> 60	< 12
B	Stable	0.54	1100	> 57	< 20
C	Stable	0.77	1550	> 54	<30
D	High density	0.93	1850	2: 46	40
E	Near capacity	1	2000	2: 30	67
F	Breakdown	Unstable		< 30	> 67

Level of service for basic freeway sections for 70 km/h design speed

Ideal conditions

The above-presented table presents the capacities and service-levels for traffic in the US under ideal conditions. The ideal conditions relate to the lane width (3.5 meters) and to the fact that it is a motorway. Thus slow traffic does not interfere with fast traffic. The maximum capacity in the US is around 2000 vehicles per lane.

Highway Capacity Manual

The *Highway Capacity Manual* proposes using the following example relation to express the influence of non-ideal conditions

$c = C_j \, N \, f_w \, f_{HV} \, f_p$

where

c = capacity (veh/h)
Cj = lane capacity under ideal conditions with design speed of *j*
N = number of lanes
f w = lane width and lateral clearance factor
f HV = heavy vehicle factor
fp = driver population factor

Effect of rain

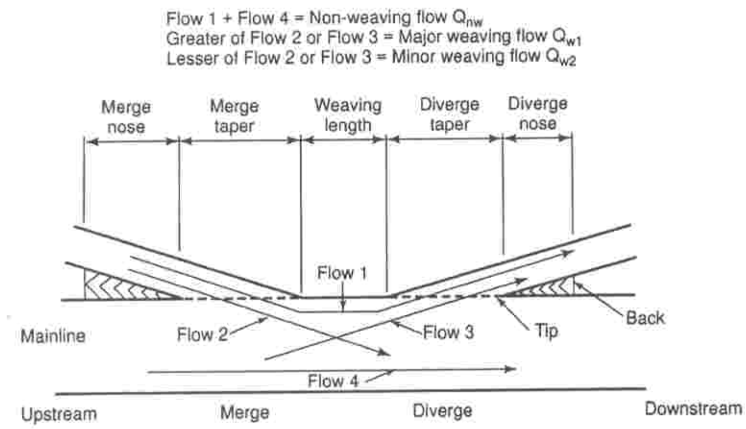
Several studies have shown that other factors (such a weather and ambient conditions) also influence the capacity significantly. For instance, the effect of rain on the capacity yields a factor of *fweather* = 0.85.
The capacity of the road is highly influenced by the behaviour of the drivers. In countries, with disciplined traffic behaviour the capacity seems to be considerable higher than in countries where traffic behaviour is less disciplined. Less disciplined traffic tend to block other traffic. Another factor are the headways that traffic is using. Headways is the distance between two vehicles in a row. In particular on motorways, it appears that the high-speed traffic with small headways, results in a high capacity of the road.

2.1.1 Ramps

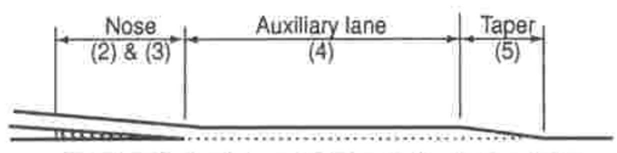
Typical ramps

Ramps are sections of roadway that provide connections from one motorway to another motorway or normal road. Entering and exiting traffic causes disturbances to the traffic on the motorway and can thus affect the capacity and level-of service of the motorway. There are basically two types of ramps:

1. Tapers
2. Parallel merger



An example of a taper

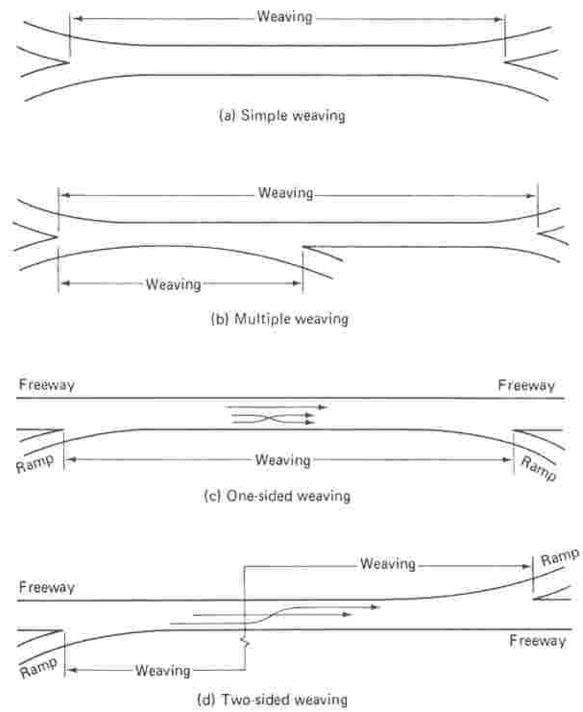


A parallel merger

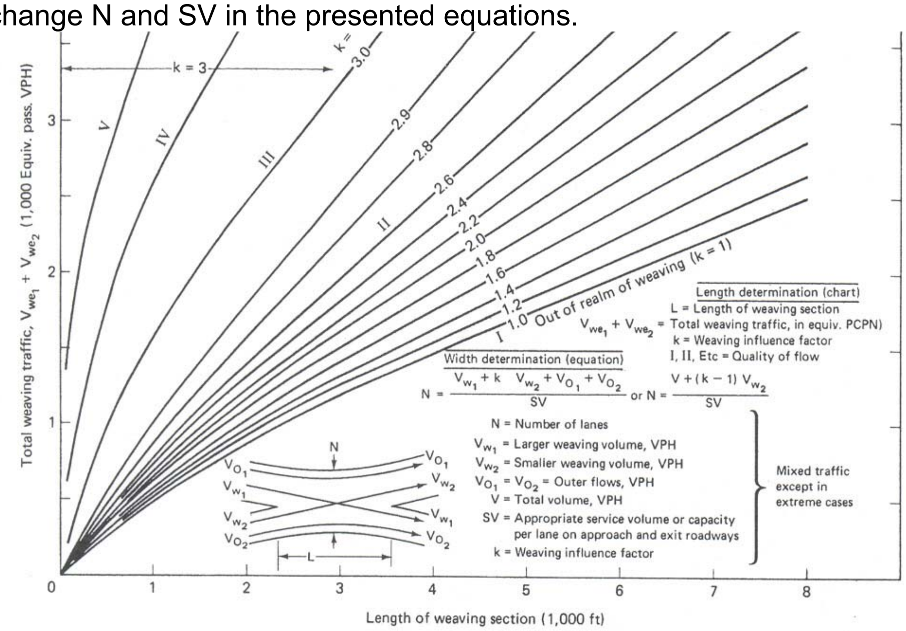
2.1.2 Weaving sections

Weaving is the crossing of traffic streams moving in the same general direction. It is accomplished through merging and diverging movements. Traffic change lanes at the weaving sections. (Ramps are in a way weaving sections)
There are several different kinds of weaving sections. The most common ones are:

- Simple weaving
- Multiple weaving
- One sided weaving
- Two-sided weaving
- Or a combination of the above mentioned



With the help of the graph below it is possible to calculate the maximum capacity of a multi lane weaving section. Note that it is necessary to change N and SV in the presented equations.



3 MULTI-TRAFFIC ROADS

Mixed traffic

The earlier section can only be applied on motorways. Motorways are roads that solely are used by motorised transport with high speeds. However the majority of the roads in low and middle-income countries are rural highways and urban roads, which are used by both slow and fast traffic. Another typical characteristic of these roads is that the traffic directions are not divided.

Rural roads

Congestion on the rural highways is very rare. Congestion in the urban areas is on the other hand very common. Most of that congestion relates to the many intersections in urban areas.

3.1 SIGNALISED INTERSECTIONS

Traffic lights

Traffic lights are installed at intersections to improve the road safety or solve certain problems with regard to capacity and delays. Traffic lights have major disadvantages; it is therefore recommendable to study the implications of the installation in detail before any final decision is taken.

Disadvantages

Negative consequences of traffic lights are among others:

- The main streams that had priority without the traffic lights will encounter delays
- Traffic lights may result in so-called rat-routing effects.
- Road users get annoyed because they have to wait
- In general it increases the average delay of all road users
- Head tail accidents may occur.

Advantages

But there are also reasons for installation of traffic lights. The first reason in this domain is that vehicles on the minor approaches have to wait to cross or merge into the main stream. The higher the flow on the main stream, the longer it takes on average before a gap occurs that is long enough to cross. If there is not sufficient space between the lanes of the main approaches, the gap has to occur in both streams simultaneously, which makes the delay disproportional longer.

If the problem is that the *delays* are too long, there is only a dependence of the flow on the main approaches. If the problem is also the building up of queues on the minor approach(es), there is also a *capacity problem.* This depends both on the flow on the main stream and the ones on the minor approaches.

Apart from the two problems mentioned above, there might be two more possible arguments for the choice of traffic lights, e.g.:

. The length of the queues might be so large that another intersection or an exit is blocked

. Busses or trams might be delayed at the intersection.

Basically there are two types of traffic lights:

1. Stationary traffic light
2. Dynamic traffic lights

Stationary traffic lights

Unlike stationary traffic lights do not react on the traffic situation. Regardless whether there are vehicles in one of the legs of the junction it will signal that vehicles may pass or have to stop. Dynamic traffic lights do react on the traffic situations and it will alter its green, yellow and red periods on basis of actual traffic demands. Most traffic lights in low-income countries are of the stationary type. The following formulas to calculate parameters of the traffic light, like delay, queue length and capacity are based for these kinds of junctions. Dynamic traffic lights are usually based on calculations with computer models.

Traffic situation

The traffic situation affects the parameters of interest considerable. The queue length, the average delay time etc are all considerable longer when the traffic is congested. Unless specified differently the formulas presented below are applicable under free-flow situations.

The first parameter of interest the delay. The number of stops and the time a vehicle has to wait at a traffic light before it can pass a junction influences the delay. The average delay can be calculated with the following formulas:

Extreme low traffic density (pedestriants and cycle lanes)

$$D_{av}=r^2/(2*C)$$

Where:
D_{av}= average delay per vehicle or pedestrian
r= time of yellow and red period per cycle [seconds]
C= cycle period [seconds]

Normal circumstances

$$D_{av}=C(1-\lambda)^2/[2*(1-y)]$$

Where:
λ= green time/cycle period ratio; g/C (g= green time [seconds])
y=I/K
I= intensity
K= capacity of leg

Under optimal circumstances, maximum capacity and traffic is not congested

$$D_{av}=0.9*\{ C(1-\lambda)^2/[2*(1-y)] + x^2/[2q(1-x)] \}$$

Where:
x= saturation level; I*C/(K*g)
q= number of arriving vehicles per second; I/3600

Queue length

The queue length can be expressed in the number of vehicles or in meters. But most traffic engineers are interested to find out if the queue is blocking another intersection, and therefore the queue length is usually expressed in meters. The total length in meters depend on the number and composition of vehicles and the average distance between two vehicles. When the composition of the vehicles is known it is relatively easy to determine the average vehicle length.

$N=q*r$

q the number of vehicles arriving at the junction per second

Under normal circumstances (no congestion) the total number of vehicles in the queue (N) is equal to number of vehicles arriving during the yellow and red period [r (sec)].

$N_b= N/\{1-(J/V)q\}$

J average length of vehicle
V Driving Speed [m/s]

Because the vehicles have a certain dimension, the location where the vehicles have to stop moves backwards. And therefore the vehicles have to stop earlier as the queue grows. Thus the number of vehicles arriving at the junction accelerates. It is therefore necessary to correct the number of vehicles in the queue.

$N_m=1.4\ N_b/(1-y)$

When the situation close to the saturation level, the queue will continue growing during the first part of the green light period. It is possible to include this behaviour to multiply N_b with 1/(1-y). It is often assumed that the arrival of the vehicles follow the Poisson distribution and therefore N_b is also multiplied with 1.4.

Capacity

The capacity of a single lane is the maximum number of vehicles that can pass the stop line of a lane. The basic saturation flow (S_0) is 1800 pce/h[1], PCE stands for passenger car equivalent. Since lorries, busses and vans need more time to pass the stop line, they have a higher PCE.

Vehicle Category	PCE value
Passenger car	1
Lorry	1.5
Articulated Lorry	2.3
Bus	2
Motor cycle	0.4
Bicycle	0.2

[1] The basic saturation flow for separate bicycle lanes and pedestrian lanes are a lot higher;

	Lane width (m)	Basic saturation flow per hour
Bicycles	1 1.8	3300 4700
Pedestriants	1 2 3	3500-5000 7000-10000 11500-15000

$S=S_0 * \beta_1 * g/C$

The saturation flow (S) is affected by the multiplication of geometric and traffic conditions as lane width, parked vehicles, turning movements etc. and the green time ratio (g/C).

Where
g, duration of the green period [seconds]
C, cycle time [seconds]
$\beta_1 = n_{lanes} * f_w * f_{HV} * f_g * f_p * f_{bb} * f_a * f_{radius} * f_{pp} * f_{comp}$
n_{lanes} Number of lanes
$f_{w,}$ adjustment factor lane width
f_{HV} adjustment factor heavy vehicles
f_g adjustment factor for grade
f_p adjustment factor for parking facilities
f_{bb} adjustment factor for bus blockage
f_a adjustment factor for area type
f_{radius} adjustment factor the radius of the turning movement
f_{comp} adjustment factor for the percentage of turning traffic
f_{pp} adjustment factor for giving way to pedestrians

Table Width adjustment factor

Lane width	2.6m	3.0	3.5	4
f_w HCM	0.88	0.94	0.99	1.03
f_w CAPCAL	0.93	1.00	1.02	1.03

Table HCM adjustment factor for heavy vehicles

Percentage Heavy Vehicles	0	2	4	6	8	10	15	20	25
f_{Hv}	1.0	0.99	0.98	0.97	0.96	0.95	0.93	0.91	0.98

Table HCM-estimate of the adjustment factor for grade

	downhill			uphill			
Grade %	**-6**	**-4**	**-2**	**0**	**+2**	**+4**	**+6**
f_a HCM	1.03	1.02	1.01	1.00	0.99	0.98	0.97
f_a CAPCAL	1.06	1.04	1.02	1.00	0.98	0.96	0.94

Table Adjustment factor for parking (HCM)

	Number of parking manoeuvres/hour					
nlanes	**Not allowed**	**0**	**10**	**20**	**30**	**40**
1	1.0	0.90	0.85	0.80	0.75	0.70
2	1.0	0.95	0.92	0.89	0.87	0.85
3	1.0	0.97	0.95	0.93	0.91	0.89

Table Adjustment factor for bus blockage

Number of lanes in lane group	Number of stopping busses per hour				
	0	**10**	**20**	**30**	**40**
1	1.00	0.96	0.92	0.88	0.83
2	1.00	0.98	0.96	0.94	0.92
3	1.00	0.99	0.97	0.96	0.94

Table Adjustment factor for area type (HCM)

Area type	Central business district	All other areas
f_{area}	0.90	1.00

Table Adjustment factor for radius of turning movement

Radius (m)	10	15	30
f_{radius}	0.9	095	0.98

Table Adjustment factor for Composition of traffic movements

Percentage of vehicles turning	10	20	30
f_{comp}	0.98	0.97	0.96

Table adjustment factor for traffic situations in which traffic has to give way to pedestrians

Number of pedestraints/hour	50	150	300	500
f_{pp}	1	0.95	0.9	0.8

3.2 ROUNDABOUTS

Types of roundabouts

Roundabouts are in many countries popular alternatives of traffic control. Its capacity is usually larger than for uncontrolled junctions and and the delays are in general less than for controlled intersections. Its most popular argument is the reduction of traffic accidents, although that depends, like the capacity, strongly on traffic rules.
The capacity of the roundabout depends also on its geometric design.

Right of way

The most popular roundabout is characterised by the fact that the circulating traffic has right of way.

Bovy

Bovy developed a model to estimate the capacities of the legs to enter the roundabout. This model can be applied for one or two lane roundabouts. The model considers both the influence of the number of lanes of the entry and the circulatory roadway.
$C_{entry} = [1500\text{-}8*(\beta*q_{circ} + \alpha * q_{exit})/9] /y$

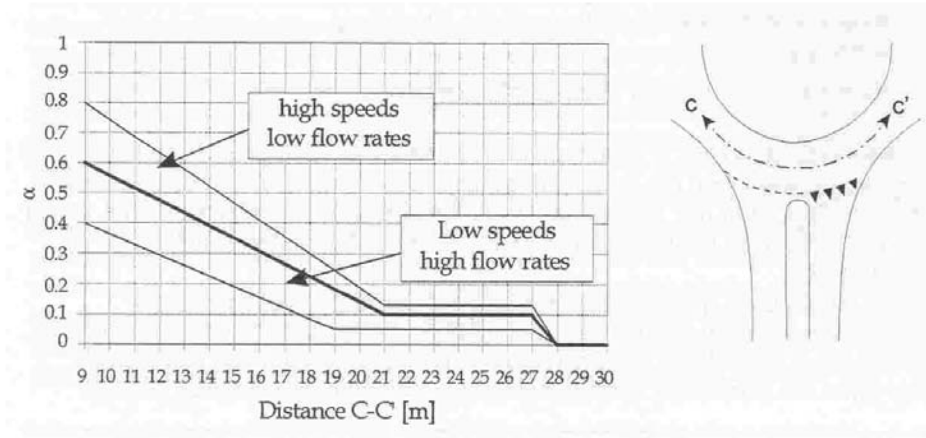
Where
$C_{entry,}$ Entry capacity (pcu/h)
β, Influence of the number of lanes of the circulatory
q_{circ} Circulating flow (pcu/h)
α, Influence of pseudo conflict
q_{exit} exiting flow (pcu/h)
y Influence of the number of lanes of the entry

Thus the model assumes a maximum entry capacity of 1500 pcu/h.

Variable	Single lane roundabout	Two lane roundabout
β	0.9 – 1.0	0.6 – 0.8
Y	1.0	0.6 – 0.7

Pseudo conflict

The essence of the pseudo conflict is that drivers at the entry sometimes wait for vehicles that in fact exit the circulatory roadway.
In other words, drivers at the entry perceive a part of the exiting flow as conflicting. Consequently, the effectively conflicting flow consists of the actually conflicting flow and a part of the exiting flow. Bovy calculates this part of the exiting flow as the product of the exiting flow and the coefficient a. This means that the impact of the pseudo conflict on capacity is larger for higher values of the exiting flow or the coefficient α. This coefficient is most significantly influenced by the geometric design of the roundabout. The geometric design determines the distance between the entry and the ultimate point where the decision to leave the roundabout becomes obvious. In Bovy's model this distance is measured between the points C and C'.



With the help of the graph it is possible to estimate the value for α.