Chapter 2
Capacity Evaluation

In the previous Sect. 1.2, the definitions of capacity $C$ of an entry, simple capacity $SC$, and whole or total capacity $TC$ were discussed.

The section also contains further definitions regarding reserve capacity indices (absolute $RC$, percentage $RC\%$, and percentage Capacity Rate $CR\%$).

As we will see in the following Sect. 2.1, the determination of Capacity $C_i$ at the entries “i” is easy if the entries are all at undersaturation conditions $(RC)_i = C_i - Q_{ei} > 0$, i.e., $\rho_i = Q_{ei}/C_i < 1 \forall i$).

On the other hand, if one or more of the entries “i” are not undersaturated, the determination of their capacities $C_i$ is not straightforward. The determinations of simple capacity $SC$ and total capacity $TC$ are not straightforward.

In all these cases, it is necessary to use specific, iterative calculation methods, which will be dealt with in the following Sects. 2.5 and 2.6.

2.1 Capacity Calculation at Steady-State Conditions

As already described, by specifying Eq. (1.16) in Chap. 1, the capacity formulas that are currently available may be classified into three types:

a) the roundabout is characterized only by its configuration, represented by the number of circle lanes and leg lanes;

b) the roundabout geometry is taken into account in somewhat detailed way;

c) we take into account, together with geometric aspects, the users’ behaviors thanks to psycho-technical times $T_c$, critical gap, and follow-up time $T_f$.

To provide some examples of the type of relationships of the above-mentioned classifications (a; b; c), six capacity formulas are now presented and implemented.

Two formulas of type (a) that were developed by Brilon et al. (Germany) and by Bovy et al. (Switzerland) are presented in which the roundabout configuration is therefore represented by the number of lanes at the entries and in the circle. In addition, according to Brilon’s formula, the disturbing flow $Q_d$ is represented only
by the circulating flow $Q_c$ in front of the entries, whereas, according to Bový’s formula, $Q_d$ is a linear combination of $Q_c$ and exiting traffic $Q_u$.\(^1\)

The third formula presented, developed by TRRL (United Kingdom), belongs to set (b) and requires, with respect to the two previous cases, a more detailed characterization of the roundabout geometry and uses the size of the main planimetric elements of the roundabout as input; in this formula, the disturbing flow is represented only by the circulating flow $Q_c$.

The fourth formula presented, the GIRABASE procedure (France), belongs to set (c). In fact, it is necessary to determine some geometric values of the roundabout and to use a pre-fixed follow-up time value $T_f$ to implement the formula. In this case, the disturbing flow is represented by a linear combination of the circulating flow with the exiting flow.

The fifth formula, developed by Brilon and Wu (Germany), belongs to set (c), and it considers capacity as a function of the roundabout configuration, rendered in terms of number of lanes at the entries and in the circle and as function of the users’ psycho-technical attitudes, expressed by determining the critical gap $T_c$ and follow-up time $T_f$\(^2\) values.

In this case, $Q_d$ is set equal to $Q_c$.

The sixth formula also belongs to set (c). It is included in the Highway Capacity Manual HCM 2002 [1].

The capacity formulas available in the literature generally express entering flows in passenger car unities (pcu/h), and, using the same measure, entry capacities are obtained.

To express flows $Q_e$ in pcu/h, vehicles other than passenger cars are generally treated as follows: 1 truck, bus = 1.5 pcu; 1 truck + trailer = 2.0 pcu; 1 motorcycle = 0.5 pcu; 1 bicycle = 0.5 pcu.

When formulas make use of the number of lanes, one should reason as follows. According to regulations that are largely accepted, circle lanes must not have road markings; for this reason, the phrase “number of circle lanes” is meant to be the number of circulating vehicles rows that can be accommodated on the circulatory roadway.

In all the following examples, we assume that all the intersections under examination are at steady-state conditions.

We wish to recall (see Sect. 1.1) that a steady-state condition, as we mean it here, is achieved if entries are undersaturated and traffic demand at each leg remains constant for a time period $T$ of a suitable size. In other words, $T$ must be long enough to allow the operating conditions of the intersection to become steady with constant mean values of state variables. In addition, the punctual values of state variables must be little dispersed around the mean values.

---

1 For $Q_e$, $Q_u$, and $Q_c$, see Fig. 1.2 in Chap. 1.

2 To evaluate $T_c$ and $T_f$, see, for example, [3].
2.1 Capacity Calculation at Steady-State Conditions

2.1.1 Brilon-Bondzio Formula (Germany)

The capacity of an entry is represented by the simple linear relationship [2, 3]

\[ C = A - B \cdot Q_c \text{ (pcu/h)} \]  \hspace{1cm} (2.1)

where A and B are obtained from Table 2.1, depending on the numbers of entry and circle lanes.

Equation (2.1) is valid for roundabouts with external diameters \( D_{\text{ext}} \) that range from 28 to 100 m.

In Eq. (2.1), the disturbing traffic \( Q_d \) coincides with the circulating flow \( Q_c \) in front of the entry for which \( C \) is determined.

Figure 2.1 shows the representation of Eq. (2.1) for all the geometric configurations for which it is valid.

As an example, consider a four-legged roundabout with a double-lane circle and double-lane entries.

<table>
<thead>
<tr>
<th>Table 2.1</th>
<th>Parameters values for Brilon-Bondzio capacity formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circle lane number</td>
<td>Entry lane number</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>2–3</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

![Fig. 2.1 Capacity C versus circulating flow Q_c according to Brilon-Bondzio capacity formula](image)
The entering flow vector (pcu/h) is \( Q_e = [322, 252, 329, 408] \).

The origin/destination matrix relative to the time considered is the following (the traffic volumes in matrix \( M_{O/D} \) are expressed in pcu/h):

\[
M_{O/D} = \begin{bmatrix}
0 & 82 & 116 & 124 \\
74 & 0 & 92 & 86 \\
106 & 96 & 0 & 127 \\
128 & 141 & 139 & 0
\end{bmatrix}
\]

From the entering flows vector \( Q_e \), with Eqs. (1.12) and (1.13) in Chap. 1, we obtain the exiting flows (\( Q_u \)) and circulating flows in front of each entry (\( Q_c \)) for each leg, i.e., \( i = 1, 2, 3, 4 \), of the roundabout:

\[
\begin{align*}
Q_{u1} &= 308 \text{ pcu/h} \\
Q_{u2} &= 319 \text{ pcu/h} \\
Q_{u3} &= 347 \text{ pcu/h} \\
Q_{u4} &= 337 \text{ pcu/h}
\end{align*}
\]

\[
\begin{align*}
Q_{c1} &= 376 \text{ pcu/h} \\
Q_{c2} &= 379 \text{ pcu/h} \\
Q_{c3} &= 284 \text{ pcu/h} \\
Q_{c4} &= 276 \text{ pcu/h}
\end{align*}
\]

On the basis of Eq. (2.1), with \( A = 1380 \) and \( B = 0.50 \) (See Table 2.1), the capacities for each entry are:

\[
\begin{align*}
C_1 &= 1380 - 0.5 \cdot Q_{c1} = 1192 \text{ pcu/h} \\
C_2 &= 1380 - 0.5 \cdot Q_{c2} = 1190 \text{ pcu/h} \\
C_3 &= 1380 - 0.5 \cdot Q_{c3} = 1238 \text{ pcu/h} \\
C_4 &= 1380 - 0.5 \cdot Q_{c4} = 1242 \text{ pcu/h}
\end{align*}
\]

Then, we evaluate the capacity indices for each entry (See Sect. 1.2).

The reserve capacities are:

\[
\begin{align*}
(RC)_1 &= C_1 - Q_{e1} = 1192 - 322 = 870 \text{ pcu/h} \\
(RC)_2 &= C_2 - Q_{e2} = 1190 - 252 = 938 \text{ pcu/h} \\
(RC)_3 &= C_3 - Q_{e3} = 1238 - 329 = 909 \text{ pcu/h} \\
(RC)_4 &= C_4 - Q_{e4} = 1242 - 408 = 834 \text{ pcu/h}
\end{align*}
\]

Percentage Capacity Rates (\( CR\% \)) for each entry are

\[
\begin{align*}
(CR\%)_1 &= (Q_{e1}/C_1) \cdot 100 = (322/1192) \cdot 100 = 27.0\% \\
(CR\%)_2 &= (Q_{e2}/C_2) \cdot 100 = (252/1190) \cdot 100 = 21.2\% \\
(CR\%)_3 &= (Q_{e3}/C_3) \cdot 100 = (329/1238) \cdot 100 = 26.6\% \\
(CR\%)_4 &= (Q_{e4}/C_4) \cdot 100 = (408/1242) \cdot 100 = 32.9\%
\end{align*}
\]
For the roundabout as a whole, the following mean values are obtained:

\[
RC = \frac{\sum_{i=1}^{n} (RC)_i \cdot Q_{ei}}{\sum_{i=1}^{n} Q_{ei}} = \frac{870 \cdot 322 + 938 \cdot 252 + 909 \cdot 329 + 834 \cdot 408}{322 + 252 + 329 + 408} \approx 881 \text{ pcu/h}
\]

\[
(CR\%) = \frac{\sum_{i=1}^{n} (CR\%)_i \cdot Q_{ei}}{\sum_{i=1}^{n} Q_{ei}} = \frac{27.0\% \cdot 322 + 21.2\% \cdot 252 + 26.6\% \cdot 329 + 32.9\% \cdot 408}{322 + 252 + 329 + 408} \approx 27.6\
\]

### 2.1.2 Bovy et al. Formula (Switzerland)

This formula is recommended for roundabouts (to be used in urban and suburban environments) with a non mountable central island, of small dimensions (maximum internal diameter \(D_{\text{int}} = 18 - 20 \text{ m}\)) [3]. The circle external diameter \(D_{\text{ext}}\) varies generally from 24 to 34 m, and there are flared entries, i.e., there are more lanes next to the stop line to make the choice of the desired direction easier.

An entry capacity is determined with the relationship:

\[
C = \frac{1}{\gamma} \cdot (1500 - \frac{8}{9} \cdot Q_d) \text{ (pcu/h)}
\]  

(2.2)

where \(\gamma\) is a parameter that allows taking into account the number of entry lanes, and its value is:

- \(\gamma = 1\) for one lane;
- \(\gamma = 0.6 - 0.7 \text{ m}\) for two lanes (according to smaller or larger entry dimensions), and it is generally set at 0.667;
- \(\gamma = 0.5\) for three lanes.

\(Q_d\) is the disturbing traffic determined as:

\[
Q_d = \alpha \cdot Q_u + \beta \cdot Q_c \text{ (pcu/h)}
\]  

(2.3)

where (See Fig. 2.2):

- \(Q_u\) = exiting traffic;
- \(Q_c\) = circulating traffic in front of the exit being considered.
Fig. 2.2 Distance $\ell$ between the exiting conflicting point (A) and entering point (B).

Coefficients $\alpha$ and $\beta$ are related to the geometry of the roundabout and take into account the distance $\ell$ between the exiting conflicting points (A) and entering points (B) that are conventionally identifiable on the circle (Fig. 2.2) and the number of circular lanes, respectively.

Due to the ability to simulate the roundabout, it was possible to establish that, in accordance with the intuitively obvious inverted proportionality relationship between $\ell$ and the percentage disturb due to the vehicles exiting the intersection, $\alpha$ decreases with $\ell$ until, for $\ell > 28$ m, the exiting vehicles do not disturb the entering vehicles ($\alpha = 0$).

Figure 2.3 shows three behaviors of the value $\alpha$ as a function of the distance $\ell$. The line “a” is relative to a circle flow speed of 20–25 km/h; lines “b” and “c” border the band above and below “a” when $V > 20–25$ km/h (greater disturb) and when $V < 20–25$ km/h (smaller disturb), respectively.
For $\beta$, which takes into account the reduction effect that the presence of more than one circle lane has on the conflicting flow caused by the circulating traffic, the following values are provided: $\beta = 0.9–1.0$ for one lane; $\beta = 0.6–0.8$ for two lanes; and $\beta = 0.5–0.6$ for three lanes.

To calculate the number of equivalent passenger car units (pcu), the following values are suggested:

- one bike or motorbike in the circle = 0.8 pcu
- one entering bike or motorbike = 0.2 pcu
- one heavy vehicle or bus = 2.0 pcu

The Swiss Standards on roundabouts use the formula proposed by Bovy et al. and use the following two capacity indices as the roundabout efficiency indicators. The calculation of these indices and their meanings are straightforward, and they must always be determined together. The calculations are performed as shown below:

- Capacity Rate used at entries (CRU$_e$):

\[
CRU_e = (\gamma \cdot Q_e/C_e) \cdot 100 \text{ (\%)} \quad (2.4)
\]

- Capacity Rate used at the conflicting point (CRU$_c$):

\[
CRU_c = [((\gamma \cdot Q_e + 8/9 \cdot Q_d)/1500) \cdot 100 \text{ (\%)}] \quad (2.5)
\]

Now, we present an example of implementation of the procedure for the roundabout examined in the previous Sect. 2.1.1 (a four-legged roundabout with a double-lane circle and double-lane entries). We assume that the distance $\ell$ between the conflicting points is equal to 20 m in front of each leg.

The traffic data are the same as the traffic data used in the example in Sect. 2.1.1.

The circle flow speed is assumed to be 20–25 km/h. The value of the parameter $\alpha$ is determined from the diagram shown in Fig. 2.3, along the line “a”, as a function of the distance $\ell = 20$ m for all the legs. The result is $\alpha = 0.14$.

Since the circle has two lanes, $\beta$ is equal to 0.7.

Thus, disturbing flows in front of the legs can be determined in the following way:

\[
Q_{d1} = \alpha \cdot Q_{u1} + \beta \cdot Q_{c1} = 0.14 \cdot 308 + 0.7 \cdot 376 \approx 307 \text{ pcu/h}
\]
\[
Q_{d2} = \alpha \cdot Q_{u2} + \beta \cdot Q_{c2} = 0.14 \cdot 319 + 0.7 \cdot 379 \approx 311 \text{ pcu/h}
\]
\[
Q_{d3} = \alpha \cdot Q_{u3} + \beta \cdot Q_{c3} = 0.14 \cdot 347 + 0.7 \cdot 284 \approx 249 \text{ pcu/h}
\]
\[
Q_{d4} = \alpha \cdot Q_{u4} + \beta \cdot Q_{c4} = 0.14 \cdot 337 + 0.7 \cdot 276 \approx 242 \text{ pcu/h}
\]
Therefore, with Eq. (2.2), we can determine the capacity values at entries, using \( \gamma = 0.667 \) for all (because of double-lane entries), as shown below:

\[
\begin{align*}
C_1 &= 1/\gamma \cdot (1500 - 8/9 \cdot Q_{d1}) = 1/0.667 \cdot (1500 - 8/9 \cdot 307) \approx 1840 \text{ pcu/h} \\
C_2 &= 1/\gamma \cdot (1500 - 8/9 \cdot Q_{d2}) = 1/0.667 \cdot (1500 - 8/9 \cdot 311) \approx 1834 \text{ pcu/h} \\
C_3 &= 1/\gamma \cdot (1500 - 8/9 \cdot Q_{d3}) = 1/0.667 \cdot (1500 - 8/9 \cdot 249) \approx 1917 \text{ pcu/h} \\
C_4 &= 1/\gamma \cdot (1500 - 8/9 \cdot Q_{d4}) = 1/0.667 \cdot (1500 - 8/9 \cdot 242) \approx 1926 \text{ pcu/h}
\end{align*}
\]

Finally, the values \( \text{CRU}_{e} \) and \( \text{CRU}_{c} \) are:

\[
\begin{align*}
\text{CRU}_{e1} &= (\gamma \cdot Q_{e1}/C_{e1}) \cdot 100 = (0.667 \cdot 322/1840) \cdot 100 = 11.7\% \\
\text{CRU}_{e2} &= (\gamma \cdot Q_{e2}/C_{e2}) \cdot 100 = (0.667 \cdot 252/1834) \cdot 100 = 9.2\% \\
\text{CRU}_{e3} &= (\gamma \cdot Q_{e3}/C_{e3}) \cdot 100 = (0.667 \cdot 329/1914) \cdot 100 = 11.4\% \\
\text{CRU}_{e4} &= (\gamma \cdot Q_{e4}/C_{e4}) \cdot 100 = (0.667 \cdot 408/1926) \cdot 100 = 14.1\% \\
\text{CRU}_{c1} &= (\gamma \cdot Q_{e1} + 8/9 \cdot Q_{d1})/1500 \cdot 100 \\
&= (0.667 \cdot 322 + 8/9 \cdot 307)/1500 \cdot 100 = 32.5\% \\
\text{CRU}_{c2} &= (\gamma \cdot Q_{e2} + 8/9 \cdot Q_{d2})/1500 \cdot 100 \\
&= (0.667 \cdot 252 + 8/9 \cdot 311)/1500 \cdot 100 = 29.6\% \\
\text{CRU}_{c3} &= (\gamma \cdot Q_{e3} + 8/9 \cdot Q_{d3})/1500 \cdot 100 \\
&= (0.667 \cdot 329 + 8/9 \cdot 249)/1500 \cdot 100 = 29.4\% \\
\text{CRU}_{c4} &= (\gamma \cdot Q_{e4} + 8/9 \cdot Q_{d4})/1500 \cdot 100 \\
&= (0.667 \cdot 408 + 8/9 \cdot 242)/1500 \cdot 100 = 32.5\%
\end{align*}
\]

2.1.3 TRRL Formula (United Kingdom)

With the TRRL formula, capacity \( C \) of a generic entry is determined as a function of the leg and circle geometric parameters and of the circulating flow in the circle \( (Q_c) \) in front of the entry [4].

The relationship was developed by Kimber, and it is based on experimental observations of a large number of operating roundabouts in England. It has the following linear form:

\[
C = k \cdot (F - f_c Q_c) \text{ (pcu/h)} \quad (2.6)
\]

where:

\[
\begin{align*}
F &= 303 \cdot x_2 \\
f_c &= 0.210 \cdot t_D \cdot (1 + 0.2 \cdot x_2) \\
k &= 1 - 0.00347 \cdot (\Phi - 30) - 0.978 \cdot (1/r - 0.05) \\
t_D &= 1 + \frac{1}{2 \cdot [1 + \exp((D - 60)/10)]} \\
x_2 &= v + \frac{(e - v)}{(1 + 2 \cdot S)} \\
S &= 1.6 \cdot (e-v)/\ell' = (e-v)/\ell
\end{align*}
\]
Table 2.2 Geometric parameters used by the TRRL formula

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Range values</th>
</tr>
</thead>
<tbody>
<tr>
<td>e</td>
<td>Entry width</td>
<td>3.6–16.5 m</td>
</tr>
<tr>
<td>v</td>
<td>Lane width</td>
<td>1.9–12.5 m</td>
</tr>
<tr>
<td>e′</td>
<td>Previous entry width</td>
<td>3.6–15.0 m</td>
</tr>
<tr>
<td>v′</td>
<td>Previous lane width</td>
<td>2.9–12.5 m</td>
</tr>
<tr>
<td>u</td>
<td>Circle width</td>
<td>4.9–22.7 m</td>
</tr>
<tr>
<td>ℓ, ℓ′</td>
<td>Flare mean length</td>
<td>1–∞ m</td>
</tr>
<tr>
<td>S</td>
<td>Sharpness of the flare</td>
<td>0–2–9</td>
</tr>
<tr>
<td>r</td>
<td>Entry bend radius</td>
<td>3.4–∞ m</td>
</tr>
<tr>
<td>Φ</td>
<td>Entry angle</td>
<td>0–77°</td>
</tr>
<tr>
<td>D = D_{ext}</td>
<td>Inscribed circle diameter</td>
<td>13.5–171.6 m</td>
</tr>
<tr>
<td>W</td>
<td>Exchange section width</td>
<td>7.0–26.0 m</td>
</tr>
<tr>
<td>L</td>
<td>Exchange section length</td>
<td>9.0–86.0 m</td>
</tr>
</tbody>
</table>

Table 2.2 shows the geometric parameters, the respective symbols used in the procedure, and their range [4].

The main indications contained in [4] for the determination of such parameters are now presented. However, this determination can sometimes be rather difficult because of the particular geometric configurations of the roundabout.

To illustrate the geometric elements that are used in the formula, it is useful to observe Figs. 2.4, 2.5, and 2.6. They are taken from the original work [4], and they show the left-side driving in the United Kingdom requiring that travel in the circle be clockwise. To apply the procedure to counterclockwise roundabouts that are used for right-side traffic, homologous symmetrical elements must be used.

The width of the entry (e) is determined along the perpendicular line traced from point A to the external edge (See Fig. 2.4).

The width of the entry lane (v) must be determined upstream of the leg widening next to the entry along the perpendicular line traced from the axis of the roadway to the external edge.

The width of the circulatory roadway (u) represents the distance between the splitter island at legs (point A) and the central island.

The entry radius (r) is the smallest bend radius of the external edge next to the entry.

The width of the weaving section (W) is the shortest distance between the central island and the external edge in the stretch between an entry and the following exit.

The weaving section (L) is defined as the shortest distance between the splitter islands at the legs of two successive entries.

The mean length of the flare can be determined using either of the two parameters ℓ or ℓ′. Figure 2.5 shows the geometric constructions for their determination. In both cases, by tracing a line parallel to the curve HA (at a distance v from it), we can determine the curve GD, which intersects the segment AB (which represents the entry width) at point D; the length ℓ corresponds to the segment CF, determined along the perpendicular line that passes through C (mean point of segment BD) of segment AB (with F as intersection point between the above-mentioned perpendicular and the curve GD); length ℓ′ corresponds to segment CF′ along a curve parallel to
Fig. 2.4 Geometric elements used in the TRRL formula [3]

Fig. 2.5 Geometric construction for the determination of $\ell$ and $\ell'$ [3]
the external edge BG and passing through C (with $F'$ as intersection point between
the above-mentioned curve and the curve GD).

Between $\ell$ and $\ell'$, the approximate relationship $\ell' = 1.6 \ell$ is valid within the
allowed variability for the practical use of geometric parameters.

The entry angle ($\Phi$), which represents the conflicting angle between the entering
flows and the circulating flows, must be determined according to the straightforward
indications shown in Fig. 2.6.

Now, we present an example of the application of the procedure.
Consider a four-legged roundabout with the following features:

- inscribed circle diameter: $D = 45$ m;
- entry width: $e = 4.8$ m;
- lane width: $v = 3.5$ m;
- flare mean length $\ell' = 25$ m;
- entry radius $r = 40$ m;
- entry angle: $\Phi = 60^\circ$.

Traffic data (expressed in pcu/h) are summarized in the matrix $O/D$:

$$
M_{O/D} = \begin{bmatrix}
0 & 150 & 300 & 200 \\
200 & 0 & 150 & 350 \\
350 & 150 & 0 & 150 \\
300 & 250 & 200 & 0
\end{bmatrix}
$$
From matrix O/D, the circulating flows in front of each entry can be obtained (Eq. (2.12)):

\[
\begin{align*}
Q_{c1} &= 600 \text{ pcu/h} \\
Q_{c2} &= 700 \text{ pcu/h} \\
Q_{c3} &= 750 \text{ pcu/h} \\
Q_{c4} &= 700 \text{ pcu/h}
\end{align*}
\]

Then, we can determine the calculation parameters of each leg using Eq. (2.6) since all of the geometric parameters relative to each entry are the same:

\[
\begin{align*}
S &= 1.6 \cdot (e - v) / \ell' = 1.6 \cdot (4.8 - 3.5) / 25 = 0.083 \\
x_2 &= v + (e - v) / (1 + 2 \cdot S) = 3.5 + (4.8 - 3.5) / (1 + 2 \cdot 0.083) = 4.615 \\
F &= 303 \cdot x_2 = 303 \cdot 4.615 = 1398 \\
t_D &= 1 + 0.5 / [1 + \exp((D - 60) / 10)] \\
&= 1 + 0.5 / [1 + \exp((45 - 60) / 10)] = 1.409 \\
f_c &= 0.210 \cdot x_2 \cdot (1 + 0.2 \cdot x_2) = 0.210 \cdot 1.409 \cdot (1 + 0.2 \cdot 4.615) = 0.569 \\
k &= 1 - 0.00347 \cdot (\Phi - 30) - 0.0978 \cdot (1/r - 0.05) \\
&= 1 - 0.00347 \cdot (60 - 30) - 0.978 \cdot (1/40 - 0.05) = 0.920
\end{align*}
\]

Therefore the capacity formula for all the legs can be written as:

\[
C = k \cdot (F - f_c Q_c) = 0.920 \cdot (1398 - 0.569 \cdot Q_c) = 1286 - 0.523 \cdot Q_c
\]

The capacity values determined for the four entries are:

\[
\begin{align*}
C_1 &= 972 \text{ pcu/h} \\
C_2 &= 919 \text{ pcu/h} \\
C_3 &= 893 \text{ pcu/h} \\
C_4 &= 919 \text{ pcu/h}
\end{align*}
\]

Among the further applications of the TRRL capacity formula, we illustrate the determination of a roundabout entry width.

The entering flow of an entry is set to \(Q_{ei} = 800 \text{ pcu/h}\); the circulating flow in front of the entry is set to \(Q_{ci} = 1100 \text{ pcu/h}\).

The geometric data relative to the entry are the following:

- inscribed circle diameter \(D = 40 \text{ m}\);
- entry lane width \(v = 7.3 \text{ m}\);
- flare mean length \(\ell' = 20 \text{ m}\);
- entry bend radius \(r = 25 \text{ m}\); and
- entry angle \(\Phi = 30^\circ\).

We want to determine the entry width “e” necessary, for example, to ensure a reserve capacity equal to the entering flow.
Therefore, we have:

\[ k = 1 - 0.00347 \cdot (30 - 30) - 0.978 \cdot (1/25 - 0.05) = 1.01 \]
\[ t_D = 1 + 0.5/[1 + \exp((40 - 60)/10)] = 1.44 \]
\[ f_c = 0.210 \cdot t_D \cdot (1 + 0.2 \cdot x_2) = 0.210 \cdot 1.44 \cdot (1 + 0.2 \cdot x_2) \]
\[ F = 303 \cdot x_2 \]

The entry capacity necessary to have a reserve capacity equal to the value of the entering flow is equal to \(2 \cdot 800 = 1600\) pcu/h.

Therefore, we have:

\[ C = k \cdot (F - f_c Q_c) \]
\[ 1600 = 1.01 \cdot [303 \cdot x_2 - 0.210 \cdot 1.44 \cdot (1 + 0.2 \cdot x_2) \cdot 1100] \]
\[ 1600 = 306.03 \cdot x_2 - 335.97 - 67.19 \cdot x_2 \]
\[ 1935.97 = 238.84 \cdot x_2 \]
\[ x_2 = 8.11 \]

On the other hand, we can also determine:

\[ S = 1.6(e - v)/\ell' = 1.6(e - 7.3)/20 \]
\[ x_2 = v + \frac{(e - v)}{(1 + 2 \cdot S)} = 7.3 + \frac{(e - 7.3)}{[1 + 2 \cdot 1.6 \cdot (e - 7.3)/20]} \]

Equating the two expressions for \(x_2\), we obtain the value of the width requested, which is \(e = 8.23\) m.

### 2.1.4 GIRABASE Formula (France)

GIRABASE is the commercial software currently used in France to determine the capacity of a roundabout. It was developed by CETE de l’Ouest of Nantes and was accepted by CERTU and by SETRA\(^3\) [5].

The final version of the formula was written after it was tested by Urbahn in Germany in 1996 and updated by Guichet in 1997.

It was developed by treating traffic data collected by observing the entries of roundabouts (operating at saturation conditions) with statistical regression techniques. In particular, GIRABASE software’s empirical regression equations are based on the counting of 63000 vehicles during 507 saturated operation periods of 5–10 min in 45 different roundabouts [6].

The procedures can be used for all types of roundabouts (from small roundabouts to large roundabouts) located in urban or rural areas, with the number of legs ranging from three to eight and with one, two, or three circle lanes and entry lanes [7].

---

Figure 2.7 shows the traffic flows and the geometric elements of the roundabout considered in the procedure; Table 2.3 shows the ranges of the geometric elements for the application of the procedure.

The formula for the determination of entry capacity (pcu/h), based on the exponential regression technique, is the following:

$$C = A \cdot e^{-C_B \cdot Q_d}$$  \hspace{1cm} (2.7)

with

$$A = \frac{3600 \cdot \left( \frac{L_e}{3.5} \right)^{0.8}}{T_f}$$  \hspace{1cm} (2.8)

$T_f =$ follow-up time $= 2.05$ s;
$L_e =$ width of the entry in proximity to the roundabout, determined perpendicularly to the entry direction (m);
$C_B =$ coefficient that is 3.525 for urban areas and 3.625 for rural areas;

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Range values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_e$</td>
<td>Entry width</td>
<td>3–11 m</td>
</tr>
<tr>
<td>$L_i$</td>
<td>Splitter island width</td>
<td>0–70 m</td>
</tr>
<tr>
<td>$L_u$</td>
<td>Exit width</td>
<td>3.5–10.5 m</td>
</tr>
<tr>
<td>$LA$</td>
<td>Circle width</td>
<td>4.5–17.5 m</td>
</tr>
<tr>
<td>$R_i$</td>
<td>Central island radius</td>
<td>3.5–87.5 m</td>
</tr>
</tbody>
</table>
2.1 Capacity Calculation at Steady-State Conditions

\[ Q_d = Q_u \cdot k_a \cdot \left(1 - \frac{Q_u}{Q_c + Q_u} \right) + Q_{ci} \cdot k_{ti} + Q_{ce} \cdot k_{te} \]  \hspace{1cm} (2.9)

\( Q_d \) = disturbing flow in front of the entry (pcu/h);
\( Q_u \) = exiting flow (pcu/h);
\( Q_c = Q_{ci} + Q_{ce} \) = circulating flow in front of the entry (pcu/h);
\( Q_{ci} \) = traffic rate \( Q_c \) on the inner circle lane (pcu/h);
\( Q_{ce} \) = traffic rate \( Q_c \) on the outer circle lane (close to the entry) (pcu/h);

\[ k_a = \begin{cases} \frac{R_i}{R_i + LA} - \frac{L_i}{L_{imax}} \text{ per } L_i < L_{imax} \\ 0 \text{ in the other cases} \end{cases} \]

\( R_i \) = central island radius (m);
\( LA \) = circle width (m);
\( L_i \) = splitter island width at legs (m);

\[ L_{imax} = 4.55 \cdot \sqrt{R_i + \frac{LA}{2}} \]

\[ k_{ti} = \min \left\{ \frac{160}{LA \cdot (R_i + LA)}, 1 \right\} \]
\[ k_{te} = \min \left\{ 1 - \frac{(LA - 8)}{LA} \cdot \left(\frac{R_i}{R_i + LA}\right)^2, 1 \right\} \]

As an example of the application of the procedure, consider a four-legged roundabout with a double-lane circle and single-lane entries, located in a rural environment. It has the following geometric features:

- external diameter: \( D_{ext} = 50 \) m;
- entry width: \( L_e = 4.0 \) m;
- splitter island width at legs: \( L_i = 7.0 \) m;
- circle width: \( LA = 10.0 \) m.

The value \( R_i \) of the central island outer radius is determined with the relationship:

\[ R_i = \frac{D_{ext} - 2 \cdot LA}{2} = 15 \text{ m} \]
Since the roundabout is located in a rural area, the coefficient $C_B$ is 3.625.

The value of parameter $A$, to be determined by means of Eq. (2.8), is the same for all entries and is equal to:

$$A = \frac{3600}{T_f} \left( \frac{L_e}{3.5} \right)^{0.8} = \frac{3600}{2.05} \left( \frac{4.0}{3.5} \right)^{0.8} = 1954$$

The traffic data from the TRRL procedure example (Sect. 2.1.3) are used here, and they are represented by the following matrix O/D:

$$M_{O/D} = \begin{bmatrix}
0 & 150 & 300 & 200 \\
200 & 0 & 150 & 350 \\
350 & 150 & 0 & 150 \\
300 & 250 & 200 & 0 
\end{bmatrix}$$

$M_{O/D}$ can be used to determine the values of the flows exiting from each leg and circulating in the circle in front of each entry:

$$Q_{u1} = 850 \text{ pcu/h} \quad Q_{c1} = 600 \text{ pcu/h}$$
$$Q_{u2} = 550 \text{ pcu/h} \quad Q_{c2} = 700 \text{ pcu/h}$$
$$Q_{u3} = 650 \text{ pcu/h} \quad Q_{c3} = 750 \text{ pcu/h}$$
$$Q_{u4} = 700 \text{ pcu/h} \quad Q_{c4} = 700 \text{ pcu/h}$$

Regarding the traffic rates $Q_{ci}$ and $Q_{ce}$, we assume that about 70% of the circulating flow travels on the outer circle lane and 30% travels on the inner circle lane in front of each entry. Thus, we have the following values:

$$Q_{ci1} = 420 \text{ pcu/h} \quad Q_{ce1} = 180 \text{ pcu/h}$$
$$Q_{ci2} = 490 \text{ pcu/h} \quad Q_{ce2} = 210 \text{ pcu/h}$$
$$Q_{ci3} = 525 \text{ pcu/h} \quad Q_{ce3} = 225 \text{ pcu/h}$$
$$Q_{ci4} = 490 \text{ pcu/h} \quad Q_{ce4} = 210 \text{ pcu/h}$$

For $k_{ti}$ and $k_{te}$ we calculate:

$$k_{ti} = \min \left\{ \frac{160}{LA \cdot (R_i + LA)} ; 1 \right\} = \min \{0.57; 1\} = 0.57$$
$$k_{te} = \min \left\{ 1 - \frac{LA - 8}{LA} \cdot \left( \frac{R_i}{R_i + LA} \right)^2 ; 1 \right\} = \min \{0.92; 1\} = 0.92$$

To determine the disturbing flows in front of each leg, we must also determine the coefficient $k_a$ that is the same for all the legs as function of $L_{imax}$

$$L_{imax} = 4.55 \cdot \sqrt{R_i + \frac{LA}{2}} = 4.55 \cdot \sqrt{15 + \frac{10}{2}} = 20.35 \text{ m} > L_i = 4.0 \text{ m}$$

$$k_a = \frac{R_i}{R_i + LA} - \frac{L_i}{L_{imax}} = \frac{15}{15 + 10} - \frac{4.0}{20.35} = 0.256$$
Therefore, with Eq. (2.9) we determine the disturbing flows in front of each leg. They are

\[ Q_{d1} = Q_{u1} \cdot k_a \cdot \left( 1 - \frac{Q_{u1}}{Q_{c1} + Q_{u1}} \right) + Q_{c1} \cdot k_{ti} + Q_{ce1} \cdot k_{te} = \]
\[ = 850 \cdot 0.256 \cdot \left( 1 - \frac{850}{420 + 850} \right) + 420 \cdot 0.57 + 180 \cdot 0.92 \]
\[ = 526 \text{ pcu/h} \]

and, similarly,

\[ Q_{d2} = 587 \text{ pcu/h} \]
\[ Q_{d3} = 634 \text{ pcu/h} \]
\[ Q_{d4} = 598 \text{ pcu/h}. \]

Finally, from Eq. (2.7), the entry capacity values

\[ C_1 = A \cdot e^{-C_B \cdot Q_{d1}} = 1954 \cdot e^{-3.625 \cdot 526} = 1151 \text{ pcu/h} \]

and, similarly,

\[ C_2 = 1082 \text{ pcu/h} \]
\[ C_3 = 1032 \text{ pcu/h} \]
\[ C_4 = 1070 \text{ pcu/h}. \]

Instead of applying the GIRABASE procedure, a simplified capacity formula is used (CERTU [8]) for urban French roundabouts. It is considered suitable for medium-sized and large-sized roundabouts (with a central island diameter from 20 to 60 m) with single-lane entries, symmetrical location of the legs, and a balanced entering traffic demand. In these cases, the entry capacity can be determined with the relationship:

\[ C = 1500 - \frac{5}{6} \cdot Q_d \]  
(2.10)

as function of the disturbing flow

\[ Q_d = a \cdot Q_c + b \cdot Q_u \]  
(2.11)

with

a. variable, as function of the central island radius, between 0.9 and 0.7 for R_i < 15 m and > 30 m, respectively.
b. variable, as function of the splitter island width at legs, between 0 and 0.3 for L_i > 15 m and L_i = 0 m, respectively.
Finally, it is worthwhile to note that, in France, the GIRABASE procedure long ago replaced the other formulas developed by various French road research centers. Therefore, even the SETRA formula (See Sect. 5.2.1), which is still used extensively by Italian engineers, is no longer used in France.

2.1.5 Brilon-Wu Formula (Germany)

In Germany, based on an idea from Tanner, in 1997, Brilon and Wu proposed the following formula for the calculation of capacity $C$ (pcu/h) of a roundabout entry (required by German Standard HBS 2001) [9]:

$$C = 3600 \cdot \left(1 - \frac{\Delta \cdot Q_c / 3600}{n_c}\right)^{n_c} \cdot \frac{n_e}{T_f} \cdot \exp \left[-Q_c / 3600 \cdot \left(T_c - \frac{T_f}{2} - \Delta\right)\right]$$  \hspace{1cm} (2.12)

where:

- $Q_c =$ circulating flow in front of the entry (pcu/h);
- $n_c =$ circle lane number;
- $n_e =$ entry lane number;
- $T_c =$ critical gap;
- $T_f =$ follow-up time;
- $\Delta =$ minimum headway between the vehicles circulating in the circle.

Therefore, according to Eq. (2.12), the capacity determination of roundabout entries is a function of the users’ behaviors, represented by the determination of the psycho-technical times $T_c$, $T_f$, and $\Delta$, as well as circulating traffic, the number of circle lanes, and the number of entry lanes.

Setting the model under the German conditions on the basis of experimental data (Brilon), the psycho-technical times have been estimated as $T_c = 4.1$ s, $T_f = 2.9$ s, and $\Delta = 2.1$ s.

Figure 2.8 shows the capacity behaviors determined using Eq. (2.12), as a function of the circulating traffic and of various geometric configurations of the roundabout ($n_e/n_c$).

Further developments of this capacity formula can be found in [9], where it is also recommended that Eq. (2.12) be used only in the case of roundabouts with a single-lane circle and single-lane entries. In the case of roundabouts that have circulatory roadways that can be used for vehicle traffic along two lines, the following relationship is used to determine the capacity $C$ (pcu/h) of an entry:

---

4The external diameter $D_{\text{ext}}$ must be between 40 and 60 m, and the central line of the circle must not be marked. In addition, the semi-practicable area around the central line must not be planned. The width of the circle must be a constant value of approximately 8, with a maximum of 10 m.
2.1 Capacity Calculation at Steady-State Conditions

Fig. 2.8 Capacity of roundabout entries according to the Brilon-Wu formula (HBS 2001)

\[ C = 3600 \cdot \frac{n_e}{T_f} \cdot \exp \left[ - \frac{Q_c}{3600} \cdot \left( T_c - \frac{T_f}{2} \right) \right] \]  

(2.13)

where:

- \( Q_c \) = circulating flow in front of the entry (pcu/h);
- \( n_e \) = parameter connected to the number of entry lanes; equal to 1 for single-lane entries and 1.4 for double-lane entries;
- \( T_c \) = critical gap = 4.3 s;
- \( T_f \) = follow-up time = 2.5 s.

As an example, we determine the entry capacity for a geometric configuration (a four-legged roundabout, with a double-lane circle and double-lane entries) and with the traffic data already presented in Sects. 2.1.1 and 2.1.2. First, we determine the circulating flows in front of each entry (Sect. 2.1.1); then we use Eq. (2.13) to determine capacity

\[ C_1 = 3600 \cdot \left( \frac{n_e}{T_f} \right) \cdot \exp \left[ - \frac{Q_{c1}}{3600} \cdot \left( T_c - \frac{T_f}{2} \right) \right] = \\
= 3600 \cdot (1.4/2.5) \cdot \exp \left[ - \frac{376}{3600} \cdot \left( 4.3 - \frac{2.5}{2} \right) \right] = 1194 \text{ pcu/h} \]

and, similarly,
\[ C_2 = 3600 \cdot (1.4/2.5) \cdot \exp\left[-379/3600 \cdot (4.3 - 2.5/2)\right] = 1191 \text{ pcu/h} \]

\[ C_3 = 3600 \cdot (1.4/2.5) \cdot \exp\left[-284/3600 \cdot (4.3 - 2.5/2)\right] = 1291 \text{ pcu/h} \]

\[ C_4 = 3600 \cdot (1.4/2.5) \cdot \exp\left[-276/3600 \cdot (4.3 - 2.5/2)\right] = 1299 \text{ pcu/h} \]

### 2.1.6 HCM 2000 Formula (USA)

The HCM 2000 approach for evaluating the entry capacities \( C \) for roundabouts is limited to schemes with one lane in the circle and one lane at the entries and with circulating flow \( Q_c \) not greater than 1200 pcu/h \[1\]. To evaluate \( C \), the following equation is used:

\[
C = \frac{Q_c e^{-Q_c T_c/3600}}{1 - e^{-Q_c T_c/3600}} \text{ (pcu/h)} \quad (2.14)
\]

where:

\( Q_c \) = circulating flow in front of the entry (pcu/h);

\( T_c \) = critical gap (s);

\( T_f \) = follow-up time (s).

Since extensive experimental data on operating roundabouts in the US were not available when the latest edition of the HCM was published, the Manual procedure gives an interval of capacity values obtained with the following values of the parameters \( T_c \) and \( T_f \).

The upper bound of Eq. (2.14) is obtained with \( T_c = 4.1 \text{ s} \) and \( T_f = 2.6 \text{ s} \), and the lower bound is obtained with \( T_c = 4.6 \text{ s} \) and \( T_f = 3.1 \text{ s} \) (See Fig. 2.9).

With the traffic data of Table 2.4, the capacities evaluated with Eq. (2.14) and with the German formula (2.1) were compared for a roundabout with one lane in the circle and one at the entries.

In this example the German formula is the following:

\[
C = 1218 - 0.74 \cdot Q_c \text{ (pcu/h)} \quad (2.15)
\]

In this case, we note that the average value between the lower and the upper bound of the capacity, evaluated by the HCM formula, is, in practice, the same as the value obtained by the German formula (2.15).

Figure 2.10 shows a comparison of two capacity formulas, the HCM capacity formula (Eq. (2.14)) and the German formula (Eq. (2.12)).

These two formulas are applied to a roundabout with single-lane entries and a single-lane circle. Equations (2.14) and (2.12) were evaluated using for \( T_c \) and \( T_f \) the values indicated by the German capacity formula (\( T_c = 4.1 \text{ s}; \ T_f = 2.9 \text{ s} \)).

We can note (See Fig. 2.9) that the American formula overestimates capacity systematically when compared to the values obtained from the German formula. This result was observed when the same geometric and traffic conditions were used,
2.1 Capacity Calculation at Steady-State Conditions

Fig. 2.9  HCM 2000 capacity formula for different values of critical gap and follow-up time

Table 2.4  Traffic data and capacity value for a roundabout

<table>
<thead>
<tr>
<th>Entry</th>
<th>Maneuver</th>
<th>Volume</th>
<th>$Q_c$</th>
<th>HCM 2000 formula</th>
<th>German formula (See Eq. 2.15)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Upper bound</td>
<td>Lower bound</td>
</tr>
<tr>
<td>1</td>
<td>Right turn</td>
<td>22</td>
<td>185</td>
<td>1198</td>
<td>992</td>
</tr>
<tr>
<td></td>
<td>Straight</td>
<td>208</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Left turn</td>
<td>164</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Right turn</td>
<td>59</td>
<td>384</td>
<td>1023</td>
<td>834</td>
</tr>
<tr>
<td></td>
<td>Straight</td>
<td>432</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Left turn</td>
<td>44</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Right turn</td>
<td>187</td>
<td>640</td>
<td>834</td>
<td>667</td>
</tr>
<tr>
<td></td>
<td>Straight</td>
<td>266</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Left turn</td>
<td>38</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Right turn</td>
<td>40</td>
<td>348</td>
<td>1054</td>
<td>862</td>
</tr>
<tr>
<td></td>
<td>Straight</td>
<td>134</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Left turn</td>
<td>13</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

as well as when users had the same psycho-technical parameters, for values of $Q_c$ greater than 300–350 pcu/h.
**2.2 Exit and Circle Capacities**

Until now, no studies have been conducted that were specifically dedicated to the determination of roundabout exit and circle capacities.

Regarding exits, field observations show that the capacity limit for each lane is in the range of 1200–1400 pcu/h.\(^5\)

Regarding the circulatory roadway, we can use the values shown in Table 2.5 concerning observations about operating roundabouts in Germany just as an indication of the values that can be expected.

**2.3 Consideration of Pedestrian Crosswalks**

In urban roundabouts, pedestrian crosswalks at legs reduce entry and exit capacities in proportion to the value of the pedestrian flow.

In current technical practice, three calculation procedures are mainly used to determine the above-mentioned entry capacity reductions, i.e., the English

---

\(^5\) In Europe, for safety reasons, double-lane exits are rarely used.
2.3 Consideration of Pedestrian Crosswalks

Table 2.5 Circle capacity values according to empirical data from operating roundabouts in Germany

<table>
<thead>
<tr>
<th>Type of roundabout</th>
<th>Number of entry lanes</th>
<th>Circle capacity [veh/h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roundabouts with single-lane circles (mini roundabouts and compact roundabouts)</td>
<td>1</td>
<td>1600</td>
</tr>
<tr>
<td>Compact roundabouts with double-lane circles</td>
<td>1</td>
<td>1600</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1600</td>
</tr>
<tr>
<td>Large roundabouts</td>
<td>1</td>
<td>2000</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2500</td>
</tr>
</tbody>
</table>

procedure (Marlow and Maycock), the German procedure (Brilon, Stuwe and Drews), and the French procedure (CETE de l’Ouest).

All three of the procedures are valid only when the assumption is made that pedestrians at pedestrian crosswalks have priority over vehicular traffic.

The English and French procedures are based on the same principles, since they both use the results of the mathematical queuing theory.

The German procedure is based on the treatment of empirical data obtained from operating roundabouts.

Regarding exits, specific formulas are not available at the present time, and, as will be discussed later, the same criteria that are used for exits are also used for entries.

2.3.1 Entry Capacities in Presence of Pedestrian Crosswalks

2.3.1.1 Marlow and Maycock Formula

First, the capacity value \( C_{ap} \) in the presence of only pedestrian flow \( Q_{ped} \) (Griffiths’ formula) is calculated [10]

\[
C_{ap} = \frac{Q_{ped}}{Q_{ped} \cdot \beta + (e^{Q_{ped} \cdot \alpha} - 1) \cdot (1 - e^{-Q_{ped} \cdot \beta})} \cdot 3600 \tag{2.16}
\]

where:

\( Q_{ped} = \) pedestrian flow (ped/s);
\( \beta = \frac{1}{C_{0}} \) (s);
$C_0 =$ capacity with pedestrian and vehicular flows equal to zero (completely empty roundabout);

$\alpha = B/v_{\text{ped}} =$ time necessary (s) to allow pedestrians to completely cross the pedestrian crosswalk, where $B$ (m) is the width of the road at the pedestrian crosswalk, and $v_{\text{ped}}$ (m/s) is the (mean) pedestrian flow speed.

The width $B$, which characterizes each entry, must be defined separately for each entry according to the roundabout geometry.

For $v_{\text{ped}}$, except for different direct determinations, one assumes $v_{\text{ped}} = 0.5–2.0$ m/s, with the suggested default value of 1.4 m/s.

Once known the value of $C_{\text{ap}}$, entry capacity $C_{\text{ped}}$, which takes into account the pedestrian flow, is

$$C_{\text{ped}} = C \cdot M$$

(2.17)

where $M$ is a reduction factor of the capacity $C$ value (veh/h) of the entry considered in absence of the pedestrian flow provided by

$$M = \frac{R^{n+2} - R}{R^{n+2} - 1}$$

(2.18)

with

$$R = \frac{C_{\text{ap}}}{C}$$

(2.19)

and “n” is equal to the number of vehicles that may be in the queuing area between the pedestrian crosswalk and the yielding line.

The term “n,” which must be determined for each entry, is a function of the mean longitudinal size of the vehicles (equal to 5–6 m); to determine n, we consider all the entry lanes, e.g., in the case of a double-lane entry and a distance of 5 m between the pedestrian crosswalk and the yielding line, $n = 2$.

Figures 2.11, 2.12, 2.13, and 2.14 show the relationship $M = M(Q_{\text{c}})$ for two urban roundabouts, i.e., a single-lane entry roundabout$^6$ (Figs. 2.11 and 2.12) and a double-lane entry roundabout$^7$ (Figs. 2.13 and 2.14). $M$ was determined with the TRRL capacity procedure (Eq. (2.6)) and with the German HBS 2001 procedure (Brilon-Wu formula) (Eq. (2.12)). All the graphs were traced for increasing pedestrian flow values $Q_{\text{ped}}$ from 100 to 800 ped/h with increments of 100 ped/h. The width of the pedestrian crosswalk $B$ was assumed to be 3.5 m and 7.5 m, for single-lane entries and double-lane entries, respectively. Pedestrian speed was set to $v_{\text{ped}} = 1.4$ m/s.

$^6$ The geometric parameter values used are as follows: $D = 34$ m; $u = 7$ m; $e = 4$ m; $v = 3$ m; $\ell' = 7.5$ m; $\Phi = 35^\circ$; $r = 20.8$ m. (The symbols for the parameter values are reported in Table 2.2.)

$^7$ The geometric parameter values used are as follows: $D = 56$ m; $u = 8$ m; $e = 8$ m; $v = 6.5$ m; $\ell' = 15.1$ m; $\Phi = 35^\circ$; $r = 32.7$ m. (The symbols for the parameter values are reported in Table 2.2.)
2.3 Consideration of Pedestrian Crosswalks

Fig. 2.11  $M = M(Q_c)$ relationship according to Marlow and Maycock for a single-lane roundabout with single-lane entries (capacity C determined by TRRL procedure)

Fig. 2.12  $M = M(Q_c)$ relationship according to Marlow and Maycock for a single-lane roundabout with single-lane entries (capacity C determined with HBS 2001 procedure)
Fig. 2.13 \( M = M(Q_c) \) relationship according to Marlow and Maycock for a roundabout with double-lane entries (capacity \( C \) determined with TRRL procedure)

Fig. 2.14 \( M = M(Q_c) \) relationship according to Marlow and Maycock for a roundabout with double-lane entries (capacity \( C \) determined with HBS 2001 procedure)
2.3 Consideration of Pedestrian Crosswalks

2.3.1.2 Brilon, Stuwe and Drews Formula

With this method, as with the method just illustrated in the previous section, the entry capacity $C$ (determined with any procedure which doesn’t include pedestrian crosswalks) is reduced by means of a factor $M$ that takes into account the effects of pedestrian crosswalks [11]:

$$ C_{ped} = C \cdot M \quad (2.20) $$

$M$ is given on the basis of entry configurations:

- **single-lane entry**

  $$ M = \frac{1119.5 - 0.715 \cdot Q_c - 0.644 \cdot Q_{ped} + 0.00073 \cdot Q_c \cdot Q_{ped}}{1069 - 0.65 \cdot Q_c} \quad (2.21) $$

- **double-lane entry**

  $$ M = \frac{1260.6 - 0.381 \cdot Q_{ped} - 0.329 \cdot Q_c}{1380 - 0.50 \cdot Q_c} \quad (2.22) $$

where

- $Q_c = \text{circulating flow in front of the entry (pcu/h)}$;
- $Q_{ped} = \text{pedestrian flow crossing the leg (ped/h)}$.

Figures 2.15 and 2.16 show the relationship $M = M(Q_c)$ for a single-lane entry roundabout (See Fig. 2.15) and a double-lane entry roundabout (See Fig. 2.16). The graphs were traced for increasing pedestrian flow values of $Q_{ped}$ from 100 to 800 ped/h with increments of 100 ped/h.

The equations that allow the determination of the reduction factor $M$ may give unrealistic results, when used outside the existence intervals of the experimental measures. Thus, for example, in the case of single-lane entry roundabouts with a small volume of pedestrians (<100 ped/h), the formulas show that when there is a marginal increase in pedestrians $Q_{ped}$, capacity also tends to increase.

However, these circumstances do not invalidate the formula, but they demand careful application.

2.3.1.3 CETE de l’Ouest Formula

Also with this procedure, entry capacity $C$ is reduced by means of a factor $F$ that takes into account the pedestrian flow [5]

$$ C_{ped} = C \cdot F \quad (2.23) $$
Fig. 2.15  $M = M(Q_c)$ relationship according to Brilon, Stuwe and Drews for a single-lane entry roundabout

Fig. 2.16  $M = M(Q_c)$ relationship according to Brilon, Stuwe and Drews for a double-lane entry roundabout
2.3 Consideration of Pedestrian Crosswalks

with

\[ F = 1 - \exp(-k \cdot Q_d \cdot \beta) \cdot [1 - \exp(-Q_{ped} \cdot T)] \]  \hspace{1cm} (2.24) \]

where:

- \( Q_d \) = disturbing traffic in front of the entry (pcu/s) (\( Q_d \) must be determined according to the capacity formula chosen, e.g., \( Q_d \) is given by Eq. (2.9) if one uses the GIRABASE procedure);
- \( Q_{ped} \) = pedestrian flow crossing the leg (ped/s);
- \( \beta = \frac{1}{C_0} \) (s);
- \( C_0 \) = capacity with pedestrian and vehicular flows equal to zero (completely empty roundabout);
- \( k \) = number of vehicles that may be in the area between the pedestrian crosswalk and the yielding line.

The previous graphs were traced for increasing pedestrian flow values \( Q_{ped} \) from 100 to 800 ped/h with increments of 100 ped/h.

Also Figure 2.17 shows the relationship \( F = F(Q_c) \) for increasing pedestrian flow values \( Q_{ped} \) from 100 to 800 ped/h with increments of 100 ped/h.

![Fig. 2.17](image)  \hspace{1cm}  \text{Fig. 2.17 } F = F(Q_c) \text{ relationship according to the CETE formula}
2.3.2 Exit Capacities in Presence of Pedestrian Crosswalks

We can reasonably assume that a heavy pedestrian flow at an exit causes a capacity reduction of the exit. At first, these effects are generally and approximately determined with the formula by Marlow and Maycock (Sect. 2.3.1.1), even though recent studies have shown that, using the equations proposed by this method, the pedestrian influence on the roundabout exit capacity is overestimated.

In conclusion, we wish to emphasize that the formulas relative to the determination of roundabout exit capacities demand careful application because they have not been specifically validated at this time.

2.4 Some Concluding Remarks on Capacity Formulations

The differences between the formulas presented in the previous sections and between these formulas and other formulas from the literature are mainly caused by the following reasons, as are the discrepancies between their capacity estimates:

– drivers’ behaviors at the intersection are due, among other things, to the extent of their experience with roundabouts on the road networks of their countries;
– roundabout geometric standards vary from nation to nation, which makes them dissimilar from configurations that have the same number of circle lanes and entry lanes;
– for the mixed traffic data used to determine and set calculation procedures. Some of these data are specific for certain environments, such as urban areas and rural areas, whereas other data are from contexts that are only generically similar to the environments from which the most significant samples come;
– the environments where the roundabouts are built are different because of varying national urban and territorial features, even though different environments are called in the same way in the different languages;
– there are correlations between the geometric variables and traffic values that can highlight or hide the role of some parameters during the experimental phase and statistical treatment of measures. Thus, these parameters may not be present in the capacity formulas.

In some countries (as in Italy and Spain), a specific formula for the determination of circular intersection capacity has not yet been defined.

Therefore, in these countries, it is essential to compare the different types of roundabouts present in the national standard (if one is available) and in foreign standards that address the same types of intersections. Thus, we can better choose the best calculation procedure for the case under examination, at least with respect to the conformity between the geometric standards and the environment.

As we have just mentioned, different nations use different classifications and nomenclature, resulting in their standards not being fully compatible or interchangeable. (See, for example, Tables 2.6 and 2.7, which compare Italian, German, and Swiss definitions).
### Table 2.6 Roundabout classification: Italian versus German nomenclatures

<table>
<thead>
<tr>
<th></th>
<th>Italian nomenclatures</th>
<th>German nomenclatures</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( D_{ext} ) (m)</td>
<td>( D_{ext} ) (m)</td>
</tr>
<tr>
<td>Mini-roundabouts</td>
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<td>13–24</td>
</tr>
<tr>
<td>Compact roundabouts</td>
<td>25–40</td>
<td>26–60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>urban: 26–35 (single-lane circle)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>rural: 30–45 (double-lane circle)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Urban and rural: 40–60 (double-lane circle)</td>
</tr>
<tr>
<td>Roundabouts</td>
<td>40–50</td>
<td>55–80</td>
</tr>
<tr>
<td>“Rotary circulation”</td>
<td>&gt;50</td>
<td>–</td>
</tr>
<tr>
<td>layout</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 2.7 Roundabout classification: Italian versus Swiss nomenclatures

<table>
<thead>
<tr>
<th></th>
<th>Italian nomenclatures</th>
<th>Swiss nomenclatures</th>
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<tbody>
<tr>
<td></td>
<td>( D_{ext} ) (m)</td>
<td>( D_{ext} ) (m)</td>
</tr>
<tr>
<td>Mini-roundabouts</td>
<td>14–25</td>
<td>14–20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(town centers, residential areas, urban areas)</td>
</tr>
<tr>
<td>Small roundabouts</td>
<td>–</td>
<td>19–25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(town centers, residential urban, and suburban areas)</td>
</tr>
<tr>
<td>Compact roundabouts</td>
<td>25–40</td>
<td>25–35</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(urban, suburban, and rural areas)</td>
</tr>
<tr>
<td>Roundabouts</td>
<td>40–50</td>
<td>–</td>
</tr>
<tr>
<td>Big roundabouts</td>
<td>–</td>
<td>&gt;35</td>
</tr>
<tr>
<td>(Swiss Standard nomenclature)</td>
<td></td>
<td>(rural areas)</td>
</tr>
<tr>
<td>“Rotary circulation”</td>
<td>&gt;50</td>
<td>–</td>
</tr>
<tr>
<td>layout</td>
<td></td>
<td>(Italian Standard nomenclature)</td>
</tr>
</tbody>
</table>
On the other hand, one must make such comparisons in order to decide which capacity relationship to use.

In fact, the users’ behaviors are not comparable when specific investigations are not available.

Finally, for engineers of a country where a capacity formulation is not available, the selection of a capacity formula is not easy and must be seriously considered.

However, when the engineers analyze the results obtained, they can use the comparison with the results derived from a different formula that has been deemed to be suitable for the case in question and/or compare the results with the ones of a traffic micro-simulation study of the roundabout.

### 2.5 Capacity Calculation at Saturation or Oversaturation

#### Conditions of Entries

If traffic demand at one or more entries equals or exceeds capacity, the system reaches a state characterized by flows coming from undersaturated entries equal to demand and from saturated or oversaturated entries equal to capacity.

Now we recall that, an entry capacity depends on the circulating flows determined by entering flows coming from the other legs of the roundabout. Therefore, the entry capacity values calculated only on the basis of traffic demand at the intersection and without taking into account the saturation or oversaturation conditions of some entries are not correct.

Thus, we will now present an iterative method for the determination of entering flows to a roundabout and the determination of the respective capacity values for saturated or oversaturated conditions at one or more entries.

This procedure is illustrated for a four-legged roundabout, but it is always valid due to the mathematical nature of the problem.

Traffic demand is known and is represented by the flow vectors \([Q_{ei}]\) and matrix \(P_{O/D}\), i.e., matrix \(M_{O/D}\) (See Sect. 1.1).

We proceed with successive calculation steps; for each step \((k)\), we determine the flow values for each leg that can actually enter the roundabout. Thus, we obtain a vector \([Q_{ei}^{(k)}]\); the iterative calculation converges very rapidly and ends when the same entering flows are reached for two successive steps, i.e., \([Q_{ei}^{(k)}] = [Q_{ei}^{(k-1)}]\).

The values represent the volumes that can enter the roundabout examined, under the restraint that one or more legs must have demands equal to or exceeding their capacities (traffic rate \(\rho_i = Q_{ei}/C_i \geq 1\), i.e., reserve capacity \(RC_i = C_i - Q_{ei} \leq 0\)).

At step \((1)\) of the procedure, we assume that the disturbing traffic is zero in front of entry 1 \((Q_{d1}^{(1)} = 0)\). Then, we determine the corresponding capacity \(C_1^{(1)}\) value and the flow \(Q_{e1}^{(1)}\) as the smaller of the calculated capacity value and traffic demand \(Q_{e1}\).

For entry 2, on the basis of flow \(Q_{e1}^{(1)}\) and traffic percentage matrix \(P_{O/D}\), we determine the disturbing traffic value \((Q_{d2}^{(1)})\), the corresponding capacity \(C_2^{(1)}\)
value, and the flow $Q_e^{(1)}$, as the smaller of the calculated capacity value and traffic demand $Q_e$.

We proceed similarly for entries 3 and 4. Thus, for entry 3, we determine the disturbing traffic ($Q_{d3}^{(1)}$) (starting with $Q_e^{(1)}$, $Q_e^{(1)}$, and the traffic percentage matrix), capacity $C_3^{(1)}$ and the flow $Q_e^{(1)}$; for entry 4, the disturbing traffic ($Q_{d4}^{(1)}$) (starting with $Q_e^{(1)}$, $Q_e^{(1)}$, $Q_e^{(1)}$ and the traffic percentage matrix), capacity $C_4^{(1)}$ and the flow $Q_e^{(1)}$. In the end, we obtain the vector $[Q_e^{(1)}]$ of the entering flows at step (1).

At step (2), we repeat the calculations starting with entry 1, and we determine the disturbing traffic ($Q_{d1}^{(2)}$) (starting with $Q_e^{(1)}$, $Q_e^{(1)}$, $Q_e^{(1)}$ and traffic percentage matrix), capacity $C_1^{(2)}$, and the flow $Q_e^{(2)}$.

We proceed similarly, using an iterative method, for all of the other entries, until we obtain the vector $[Q_e^{(2)}]$ of the entering flows at step (2).

Regarding, in particular, the determination of disturbing flow $Q_{di}^{(k)}$ for the generic leg “i” at step (k) of the iterative method, it is worth emphasizing that it must be determined by means of the “most recent” values of the volumes that may enter the roundabout from the other entry; thus, for example, for $Q_{d2}^{(2)}$, one uses the flow values $Q_e^{(2)}$, $Q_e^{(1)}$, and $Q_e^{(1)}$; for $Q_{d3}^{(2)}$, one uses $Q_e^{(2)}$, $Q_e^{(2)}$, and $Q_e^{(1)}$, and so the process continues until it is completed.

We proceed similarly, using an iterative method, for the following calculation steps. Thus, we obtain a succession of vectors of entering flows $[Q_e^{(3)}]$, ..., $[Q_e^{(k)}]$; as already discussed, the calculation converges very rapidly and ends when the same entering volumes ($[Q_e^{(k-1)}] = [Q_e^{(k)}]$) occur for two successive steps and the same disturbing flows ($[Q_{di}^{(k-1)}] = [Q_{di}^{(k)}]$) and capacities ($C_i^{(k-1)} = C_i^{(k)}$) are reached.

Thus, we have determined the respective capacity values taking into account the entering flow values at the intersection and the saturation or oversaturation conditions of some of the entries. In particular, it is worth noting that, for the saturated or oversaturated legs, the capacity values $C_i$ evidently coincide with those of the volumes $Q_e$ that may enter the roundabout.

### 2.5.1 A Worked Example

We will now present an application of the procedure just illustrated. For the sake of simplicity, we use a capacity formula for which the disturbing traffic $Q_d$ consists only of the circulating flow $Q_c$ in front of the entries ($Q_d = Q_c$). However, the procedure can be used without difficulty, even when $Q_d$ is also function of the exiting flow of the leg. (See, for example, Eq. (2.9)).

Consider a four-legged roundabout for which the “traffic percentage matrix” is:

$$
P_{O/D} = 
\begin{bmatrix}
0.00 & 0.31 & 0.38 & 0.31 \\
0.24 & 0.00 & 0.44 & 0.32 \\
0.36 & 0.40 & 0.00 & 0.24 \\
0.30 & 0.30 & 0.40 & 0.00
\end{bmatrix}
$$
The traffic demand vector (pcu/h) is

\[ [Q_{ei}] = [800 \ 500 \ 900 \ 700] \]

Therefore, the matrix O/D is

\[
\begin{bmatrix}
0 & 248 & 304 & 248 \\
120 & 0 & 220 & 160 \\
324 & 360 & 0 & 216 \\
210 & 210 & 280 & 0
\end{bmatrix}
\]

Among the roundabout capacity formulas available in the literature, we use the Brilon-Bondzio formula (2.1), as an example,

\[
C = A - B \cdot Q_c
\]

which is specialized for roundabouts with a single-lane circle and single-lane legs (\(A = 1218, B = 0.74\)).

Starting with traffic data, we determine the circulating flow vector \([Q_{ci}]\) (pcu/h) (Eq. (1.12) in Chap. 1).

\[ [Q_{ci}] = [850 \ 832 \ 528 \ 804] \]

The capacity vector (pcu/h), determined through the application of the above-mentioned formula for each leg, is

\[ [C_i] = [589 \ 602 \ 827 \ 623] \]

Comparing the traffic demand vector \([Q_{ei}]\) to the capacity vector \([C_i]\), we can notice that entries 1, 3, and 4 are at oversaturation conditions \((\rho_i = [Q_i/C_i] = [1.36 \ 0.83 \ 1.09 \ 1.12])\).

As already discussed, the circulating flow values and, therefore, the capacity values just determined are not correct under such conditions. In fact, the actual flow entering the oversaturated legs is not equal to demand, but to capacity.

Therefore, if one or more entries are saturated, we use the procedure calculation to determine a balanced situation.

For entry 1, if we assume at step (1) that \(Q_{c1}^{(1)} = 0\), then we obtain \(C_1^{(1)} = 1218 - 0.74 \cdot Q_{c1}^{(1)} = 1218 - 0.74 \cdot 0 = 1218\) pcu/h and \(Q_{e1}^{* (1)} = \min (C_1^{(1)}; Q_{e1}) = \min (1218; 800) = 800\) pcu/h.
This volume is divided into the following, on the basis of the traffic percentage matrix:

\[ Q_{12}^{*} = P_{12} \cdot Q_{c1}^{*} = 0.31 \cdot 800 = 248 \text{ pcu/h} \]
\[ Q_{13}^{*} = P_{13} \cdot Q_{c1}^{*} = 0.38 \cdot 800 = 304 \text{ pcu/h} \]
\[ Q_{14}^{*} = P_{14} \cdot Q_{c1}^{*} = 0.31 \cdot 800 = 248 \text{ pcu/h} \]

For entry 2, we determine

\[ Q_{c2}^{(1)} = Q_{13}^{*} + Q_{14}^{*} = 304 + 248 = 552 \text{ pcu/h} \]
\[ C_{2}^{(1)} = 1218 - 0.74 \cdot Q_{c2}^{(1)} = 1218 - 0.74 \cdot 552 = 810 \text{ pcu/h} \]
\[ Q_{e2}^{(1)} = \min (C_{2}^{(1)}, Q_{e2}) = \min (810, 500) = 500 \text{ pcu/h} \]

This volume is divided into the following, on the basis of the traffic percentage matrix:

\[ Q_{21}^{*} = P_{21} \cdot Q_{c2}^{*} = 0.24 \cdot 500 = 120 \text{ pcu/h} \]
\[ Q_{23}^{*} = P_{23} \cdot Q_{c2}^{*} = 0.44 \cdot 500 = 220 \text{ pcu/h} \]
\[ Q_{24}^{*} = P_{24} \cdot Q_{c2}^{*} = 0.32 \cdot 500 = 160 \text{ pcu/h} \]

For entry 3, we determine

\[ Q_{c3}^{(1)} = Q_{14}^{*} + Q_{21}^{*} + Q_{24}^{*} = 248 + 120 + 160 = 528 \text{ pcu/h} \]
\[ C_{3}^{(1)} = 1218 - 0.74 \cdot Q_{c3}^{(1)} = 1218 - 0.74 \cdot 528 = 827 \text{ pcu/h} \]
\[ Q_{e3}^{(1)} = \min (C_{3}^{(1)}, Q_{e3}) = \min (827, 900) = 827 \text{ pcu/h} \]

This volume is divided into:

\[ Q_{31}^{*} = P_{31} \cdot Q_{c3}^{*} = 0.36 \cdot 827 = 298 \text{ pcu/h} \]
\[ Q_{32}^{*} = P_{32} \cdot Q_{c3}^{*} = 0.40 \cdot 827 = 331 \text{ pcu/h} \]
\[ Q_{34}^{*} = P_{34} \cdot Q_{c3}^{*} = 0.24 \cdot 827 = 198 \text{ pcu/h} \]

For entry 4, we determine

\[ Q_{c4}^{(1)} = Q_{21}^{*} + Q_{31}^{*} + Q_{32}^{*} = 120 + 298 + 331 = 749 \text{ pcu/h} \]
\[ C_{4}^{(1)} = 1218 - 0.74 \cdot Q_{c4}^{(1)} = 1218 - 0.74 \cdot 749 = 664 \text{ pcu/h} \]
\[ Q_{e4}^{(1)} = \min (C_{4}^{(1)}, Q_{e4}) = \min (664, 700) = 664 \text{ pcu/h} \]

This volume is divided into:

\[ Q_{41}^{*} = P_{41} \cdot Q_{c4}^{*} = 0.30 \cdot 664 = 199 \text{ pcu/h} \]
\[ Q_{42}^{*} = P_{42} \cdot Q_{c4}^{*} = 0.30 \cdot 664 = 199 \text{ pcu/h} \]
\[ Q_{43}^{*} = P_{43} \cdot Q_{c4}^{*} = 0.40 \cdot 664 = 266 \text{ pcu/h} \]
Table 2.8  Circulating flows \([Q_{ci}]\), capacity \([C_i]\), entering flows \([Q_{ei}^*]\), and matrix \([M_{O/D}^*]\) at step (1) of the iterative method

<table>
<thead>
<tr>
<th>Leg</th>
<th>([Q_{ci}^{(1)}])</th>
<th>([C_i^{(1)}])</th>
<th>([Q_{ei}^{* (1)}])</th>
<th>O</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>1218</td>
<td>800</td>
<td>1</td>
<td>0</td>
<td>248</td>
<td>304</td>
<td>248</td>
</tr>
<tr>
<td>2</td>
<td>552</td>
<td>810</td>
<td>500</td>
<td>2</td>
<td>120</td>
<td>0</td>
<td>220</td>
<td>160</td>
</tr>
<tr>
<td>3</td>
<td>528</td>
<td>827</td>
<td>827</td>
<td>3</td>
<td>298</td>
<td>331</td>
<td>0</td>
<td>198</td>
</tr>
<tr>
<td>4</td>
<td>749</td>
<td>664</td>
<td>664</td>
<td>4</td>
<td>199</td>
<td>199</td>
<td>266</td>
<td>0</td>
</tr>
</tbody>
</table>

For step (1), Table 2.8 shows the circulating flow values \([Q_{ci}]\), capacity values \([C_i]\), entering flow values \([Q_{ei}^*]\), and matrix \([M_{O/D}^*]\).

The calculations proceed in an iterative way; in particular, it is worth noting that, as already discussed, the circulating flow \(Q_{ci}^{(k)}\) in front of the generic leg “i” at step \((k)\) of the procedure must be determined by means of the “most updated” values of the volumes that may enter the roundabout from the other legs, based on the previous calculation steps.

For entry 1, we obtain

\[
Q_{c1}^{(2)} = Q_{42}^{(1)} + Q_{43}^{(1)} + Q_{32}^{(1)} = 199 + 266 + 331 = 796 \text{ pcu/h}
\]

\[
C_1^{(2)} = 1218 - 0.74 \cdot Q_{c1}^{(2)} = 1218 - 0.74 \cdot 796 = 629 \text{ pcu/h}
\]

\[
Q_{ei}^{* (2)} = \min (C_1^{(2)}, Q_{ei}^1) = \min (629, 800) = 629 \text{ pcu/h}
\]

and therefore

\[
Q_{12}^{* (2)} = P_{12} \cdot Q_{ei}^{* (2)} = 0.31 \cdot 629 = 195 \text{ pcu/h}
\]

\[
Q_{13}^{* (2)} = P_{13} \cdot Q_{ei}^{* (2)} = 0.38 \cdot 629 = 239 \text{ pcu/h}
\]

\[
Q_{14}^{* (2)} = P_{14} \cdot Q_{ei}^{* (2)} = 0.31 \cdot 629 = 195 \text{ pcu/h}
\]

Similarly, for entry 2 we determine

\[
Q_{c2}^{(2)} = Q_{13}^{* (2)} + Q_{14}^{* (2)} + Q_{43}^{(1)} = 239 + 195 + 266 = 700 \text{ pcu/h}
\]

\[
C_2^{(2)} = 1218 - 0.74 \cdot Q_{c2}^{(2)} = 1218 - 0.74 \cdot 700 = 700 \text{ pcu/h}
\]

\[
Q_{ei}^{* (2)} = \min (C_2^{(2)}, Q_{ei}^2) = \min (700; 500) = 500 \text{ pcu/h}
\]

and therefore

\[
Q_{21}^{* (2)} = P_{21} \cdot Q_{ei}^{* (2)} = 0.24 \cdot 500 = 120 \text{ pcu/h}
\]

\[
Q_{23}^{* (2)} = P_{23} \cdot Q_{ei}^{* (2)} = 0.44 \cdot 500 = 220 \text{ pcu/h}
\]

\[
Q_{24}^{* (2)} = P_{24} \cdot Q_{ei}^{* (2)} = 0.32 \cdot 500 = 160 \text{ pcu/h}
\]
For entry 3, we have

\[ Q_{c3}^{(2)} = Q_{14}^{* (2)} + Q_{21}^{* (2)} + Q_{24}^{* (2)} = 195 + 120 + 160 = 475 \text{ pcu/h} \]

\[ C_3^{(2)} = 1218 - 0.74 \cdot Q_{c3}^{(2)} = 1218 - 0.74 \cdot 475 = 867 \text{ pcu/h} \]

\[ Q_{e3}^{* (2)} = \min(C_3^{(2)}, Q_{e3}) = \min(867, 900) = 867 \text{ pcu/h} \]

and therefore

\[ Q_{31}^{* (2)} = P_{31} \cdot Q_{e3}^{* (2)} = 0.36 \cdot 867 = 312 \text{ pcu/h} \]
\[ Q_{32}^{* (2)} = P_{32} \cdot Q_{e3}^{* (2)} = 0.40 \cdot 867 = 347 \text{ pcu/h} \]
\[ Q_{34}^{* (2)} = P_{34} \cdot Q_{e3}^{* (2)} = 0.24 \cdot 867 = 208 \text{ pcu/h} \]

Finally, we determine for entry 4

\[ Q_{c4}^{(2)} = Q_{21}^{* (2)} + Q_{31}^{* (2)} + Q_{32}^{* (2)} = 120 + 312 + 346 = 778 \text{ pcu/h} \]

\[ C_4^{(2)} = 1218 - 0.74 \cdot Q_{c4}^{(2)} = 1218 - 0.74 \cdot 778 = 642 \text{ pcu/h} \]

\[ Q_{e4}^{* (2)} = \min(C_4^{(2)}, Q_{e4}) = \min(642, 700) = 642 \text{ pcu/h} \]

and therefore

\[ Q_{41}^{* (2)} = P_{41} \cdot Q_{e4}^{* (2)} = 0.30 \cdot 642 = 193 \text{ pcu/h} \]
\[ Q_{42}^{* (2)} = P_{42} \cdot Q_{e4}^{* (2)} = 0.30 \cdot 642 = 193 \text{ pcu/h} \]
\[ Q_{43}^{* (2)} = P_{43} \cdot Q_{e4}^{* (2)} = 0.40 \cdot 642 = 257 \text{ pcu/h} \]

For step (2), Table 2.9 shows the circulating flow values \([Q_{ci}]\), capacity values \([C_i]\), entering flow values \([Q_{ei}^*]\), and matrix \(M^*_{O/D}\).

Proceeding similarly for the successive calculation phases, we obtain the values shown in Tables 2.10 and 2.11 (steps (3) and (4)).

**Table 2.9** Circulating flows \([Q_{ci}]\), capacity \([C_i]\), entering flows \([Q_{ei}^*]\), and matrix \(M^*_{O/D}\) at step (2) of the iterative method

<table>
<thead>
<tr>
<th>Leg</th>
<th>(Q_{ci}^{(2)})</th>
<th>(C_i^{(2)})</th>
<th>(Q_{ei}^{*(2)})</th>
<th>O</th>
<th>D</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
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<td>629</td>
<td>629</td>
<td></td>
<td>1</td>
<td>195</td>
<td>239</td>
<td>195</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>700</td>
<td>700</td>
<td>500</td>
<td></td>
<td>2</td>
<td>120</td>
<td>0</td>
<td>220</td>
<td>160</td>
</tr>
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<td>867</td>
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<td>3</td>
<td>312</td>
<td>346</td>
<td>0</td>
<td>208</td>
</tr>
<tr>
<td>4</td>
<td>778</td>
<td>642</td>
<td>642</td>
<td></td>
<td>4</td>
<td>193</td>
<td>193</td>
<td>256</td>
<td>0</td>
</tr>
</tbody>
</table>
Table 2.10 Circulating flows \([Q_{ci}]\), capacity \([C_i]\), entering flows \([Q_{ei}^*]\), and matrix \(M_{O/D}^*\) at step (3) of the iterative method

<table>
<thead>
<tr>
<th>Leg</th>
<th>(Q_{ci}^{(3)})</th>
<th>(C_i^{(3)})</th>
<th>(Q_{ei}^{*(3)})</th>
<th>D</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>796</td>
<td>629</td>
<td>629</td>
<td>1</td>
<td>0</td>
<td>195</td>
<td>239</td>
<td>195</td>
</tr>
<tr>
<td>2</td>
<td>691</td>
<td>707</td>
<td>500</td>
<td>2</td>
<td>120</td>
<td>0</td>
<td>220</td>
<td>160</td>
</tr>
<tr>
<td>3</td>
<td>475</td>
<td>867</td>
<td>867</td>
<td>3</td>
<td>312</td>
<td>347</td>
<td>0</td>
<td>208</td>
</tr>
<tr>
<td>4</td>
<td>778</td>
<td>642</td>
<td>642</td>
<td>4</td>
<td>193</td>
<td>193</td>
<td>256</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2.11 Circulating flows \([Q_{ci}]\), capacity \([C_i]\), entering flows \([Q_{ei}^*]\), and matrix \(M_{O/D}^*\) at step (4) of the iterative method

<table>
<thead>
<tr>
<th>Leg</th>
<th>(Q_{ci}^{(4)})</th>
<th>(C_i^{(4)})</th>
<th>(Q_{ei}^{*(4)})</th>
<th>D</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
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<td>629</td>
<td>629</td>
<td>1</td>
<td>0</td>
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<td>2</td>
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<td>0</td>
<td>208</td>
</tr>
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<td>4</td>
<td>778</td>
<td>642</td>
<td>642</td>
<td>4</td>
<td>193</td>
<td>193</td>
<td>256</td>
<td>0</td>
</tr>
</tbody>
</table>

At calculation steps (3) and (4), the entering flow vectors \([Q_{ei}^*]\), circulating flow vectors \([Q_{ci}^*]\), and capacity vectors \([C_i]\) coincide.\(^8\)

The iterative process converges, i.e., \([Q_{ei}^*] = [629 500 867 642]\) is the flow vector that enters the roundabout taking into account the oversaturation of entries 1, 3, and 4; \([C_i^*] = [629 707 867 642]\) is the capacity vector.

As already pointed out, we can notice that, for oversaturated entries, the flow values that may enter the roundabout are equal to the capacity values of the respective entries. On the other hand, for entry 2, which is at undersaturation conditions, the entering flow value is equal to traffic demand.

### 2.6 Calculation Procedures for Simple Capacity and Total Capacity

As already pointed out in Sect. 1.2, roundabout performance indicators as a whole are, in technical practice, “simple capacity” SC and “whole capacity” or “total capacity” TC.

The determinations of SC and TC are not straightforward, and they require the development of suitable computational procedures.

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\(^8\) The iterative results and the final results are all given approximated integers.
For the sake of simplicity, but without narrowing our general aims, we will now present these procedures for a four-legged roundabout with an assigned traffic demand (initial condition) represented by the flow vector \([Q_{ei}]\) and by matrix \(P_{O/D}\) (i.e., matrix \(M_{O/D}\)).

To calculate simple capacity means to determine a specific condition that is characterized by equivalence between demand and capacity values for at least one of the entries. This is done by means of a uniform increase in entering flow from an initial traffic state.

1) we calculate the disturbing flows \([Q_{di}]\) for each entry starting with the demand vector \([Q_{ei}]\) and traffic percentage matrix \(P_{O/D}\);

2) for each entry, we express the entering flow and disturbing flow values under saturation conditions as the multiplication of traffic demand by a suitable multiplier (different for each entry), i.e., \(Q_{ei}^* = \delta_i Q_{ei}\) and \(Q_{di}^* = \delta_i Q_{di}\). Thus, the generic capacity formula used for the calculation can be written as \(\delta_i Q_{ei} = f_i(\delta_i Q_{di})\). Solving these equations, we obtain the values of the multipliers \(\delta_i\) (one for each entry) of traffic demands at legs when these same legs are saturated;

3) we multiply demand vector \([Q_{ei}]\) by the smallest multiplier that we have found (corresponding to the first one that reaches saturation), and, thus, we determine simple capacity \(SC\).

To determine total capacity, we use the following iterative method:

1) we assume an arbitrary, first-attempt, entering flow vector \([Q^{(1)}_{ei}] = [Q^{(1)}_{e1} Q^{(1)}_{e2} Q^{(1)}_{e3} Q^{(1)}_{e4}]\);

2) for entry 1 we determine the disturbing traffic \(Q^{(1)}_{d1}\) as a function of the first attempt flow vector \([Q^{(1)}_{ei}]\) and matrix \([P_{ij}]\), and, by the capacity formula used, we determine a new value of entering flow 1 \(Q^{(2)}_{e1}\);

3) for entries 2, 3, and 4, we proceed similarly. First, we determine the disturbing flows (using the most “updated” entering flows for each leg, i.e., those obtained with the application of the iterative method). Then, by means of the capacity formula, we determine the new entering flow values, obtaining for them a second vector \([Q^{(2)}_{ei}]\);

4) we repeat the calculation process until we obtain, for two successive steps, two entering flow vectors that are equal, i.e., when \([Q^{(k-1)}_{ei}] = [Q^{(k)}_{ei}]\).

The entering flow vector thus determined represents the number of the entering vehicles from each leg when all the entries are simultaneously saturated. The roundabout total capacity value \(TC\) is the sum of all these flows.

Finally, it is worth noting that total capacity is a function only of the traffic percentage matrix \(P_{O/D}\), and, therefore, it can be determined starting with an arbitrary demand vector. In other words, with equal percentage distribution, total capacity
vector is univocal, independently of the demand vector used for the first calculation step (first-attempt demand vector). Contrary to total capacity, it should be noted that simple capacity is function of both traffic demand and its percentage distribution (vector \([Q_{ei}]\) and matrix \(P_{O/D}\)).

2.6.1 A Worked Example

We will now present an example calculation of simple capacity and total capacity. Consider a four-legged roundabout with a traffic percentage matrix \(P_{O/D}\) of:

\[
P_{O/D} = \begin{bmatrix}
0.00 & 0.15 & 0.75 & 0.10 \\
0.19 & 0.00 & 0.24 & 0.57 \\
0.63 & 0.15 & 0.00 & 0.22 \\
0.19 & 0.74 & 0.07 & 0.00 \\
\end{bmatrix}
\]

We use the Brilon-Bondzio (2.1) formula as the capacity formula.

\[C = A - B \cdot Q_c\]

This formula is specialized for roundabouts with a single-lane circle and single-lane legs (\(A = 1218, B = 0.74\)).

Traffic demand vector (pcu/h) is equal to

\([Q_{ei}] = [160 \ 100 \ 240 \ 200]\)

2.6.1.1 Simple Capacity Calculation

To calculate simple capacity, we first determine the circulating flow vector \([Q_{ci}]\) (pcu/h). (Eq. (1.12) in Chap. 1).

\([Q_{ci}] = [198 \ 150 \ 92 \ 206]\)

For each entry, we look for the initial flow multiplier that causes saturation at the entry by means of the relationship \(\delta_{i}Q_{ei} = A - B \cdot \delta_{i}Q_{ci}\), which, when applied to the case under examination, becomes

\[
\begin{align*}
\delta_1 \cdot 160 &= 1218 - 0.74 \cdot \delta_1 \cdot 198 \\
\delta_2 \cdot 100 &= 1218 - 0.74 \cdot \delta_2 \cdot 150 \\
\delta_3 \cdot 240 &= 1218 - 0.74 \cdot \delta_3 \cdot 92 \\
\delta_4 \cdot 200 &= 1218 - 0.74 \cdot \delta_4 \cdot 206 
\end{align*}
\]
from which we have

\[
\begin{align*}
\delta_1 &= 3.97 \\
\delta_2 &= 5.77 \\
\delta_3 &= 3.95 \\
\delta_4 &= 3.46
\end{align*}
\]

Multiplying traffic demand \([Q_{ei}]\) by the smaller multiplier (\(\delta_4 = 3.46\)), we determine the entering flow values that correspond to the first roundabout congestion event for a uniform increase in the flows (i.e., simple capacity) \([Q_{ei}^{(SC)}] = [SC]\) (pcu/h):

\[
[Q_{ei}^{(SC)}] = [SC] = [553 346 829 691]
\]

Under traffic conditions for which entering flow values are equal to simple capacity, we can also determine the circulating flow values (pcu/h) in front of the entries.

\[
[Q_{ci}^{(SC)}] = [684 518 318 712]
\]

capacities (pcu/h)

\[
[C^{(SC)}] = [712 834 983 691]
\]

and reserve capacities (pcu/h)

\[
[RC^{(SC)}] = [159 489 153 0]
\]

It is worth noting that, under this traffic condition, the reserve capacity is zero for the leg (in the case under examination, leg n° 4) that reaches the saturation state first.

### 2.6.1.2 Total Capacity Calculation

To calculate total capacity, we can randomly choose the first-attempt, entering flow vector.

For the case under examination, we assume

\[
[Q_{ei}^{(1)}] = [100 220 300 300]
\]

Then, we determine the circulating volume in front of entry 1

\[
Q_{c1}^{(1)} = (P_{42} + P_{43}) \cdot Q_{e4}^{(1)} + P_{32} \cdot Q_{e3}^{(1)} = (0.74 + 0.07) \cdot 300 + 0.15 \cdot 300 = 288
\]

and, by the capacity formula, a new entering flow value at leg 1 (in pcu/h)

\[
Q_{e1}^{(2)} = 1218 - 0.74 \cdot Q_{c1}^{(1)} = 1218 - 0.74 \cdot 288 = 1005 \text{ pcu/h}
\]
We proceed similarly for entries 2, 3, and 4. We use the “most updated” entering traffic flows coming from the various legs to calculate the conflict flows:

\[
Q_{e2}^{(1)} = (P_{13} + P_{14}) \cdot Q_{e1}^{(2)} + P_{43} \cdot Q_{e4}^{(1)} = (0.75 + 0.10) \cdot 1005 + 0.07 \cdot 300 = 875 \text{ pcu/h}
\]

\[
Q_{e2}^{(2)} = 1218 - 0.74 \cdot Q_{e2}^{(1)} = 1218 - 0.74 \cdot 875 = 570 \text{ pcu/h}
\]

\[
Q_{e3}^{(1)} = (P_{24} + P_{21}) \cdot Q_{e2}^{(2)} + P_{14} \cdot Q_{e1}^{(2)} = (0.57 + 0.19) \cdot 570 + 0.10 \cdot 1005 = 534 \text{ pcu/h}
\]

\[
Q_{e3}^{(2)} = 1218 - 0.74 \cdot Q_{e3}^{(1)} = 1218 - 0.74 \cdot 534 = 823 \text{ pcu/h}
\]

\[
Q_{e4}^{(1)} = (P_{31} + P_{32}) \cdot Q_{e3}^{(2)} + P_{21} \cdot Q_{e2}^{(2)} = (0.63 + 0.15) \cdot 823 + 0.19 \cdot 570 = 750 \text{ pcu/h}
\]

\[
Q_{e4}^{(2)} = 1218 - 0.74 \cdot Q_{e4}^{(1)} = 1218 - 0.74 \cdot 750 = 663 \text{ pcu/h}
\]

Thus, we obtain a second entering flow vector (pcu/h)

\[
[Q_{ei}^{(2)}] = [1005 \ 570 \ 823 \ 663]
\]

We proceed similarly, and we obtain

\[
[Q_{ei}^{(3)}] = [729 \ 725 \ 756 \ 680]
\]

\[
[Q_{ei}^{(4)}] = [727 \ 726 \ 756 \ 680]
\]

\[
[Q_{ei}^{(5)}] = [727 \ 726 \ 756 \ 680]
\]

The iterative process converges very rapidly. The entering flow vectors determined for steps (4) and (5) are equal, and they represent the number of vehicles that each leg is able to serve when all the legs are saturated.

The sum of all these flows provides the roundabout total capacity TC, which is 2888 pcu/h.

References

Calculation of Roundabouts
Capacity, Waiting Phenomena and Reliability
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