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ROUNDABOUT DESIGN CRITERIA: AN INTERNATIONAL OVERVIEW

Roundabouts are hastily spreading around the world, mainly because of their good safety performance, and several countries have recently updated their standards and guidelines. However, inconsistencies in design standards and practices are observed.

In this paper, a critical review of the Australasian, EU and US standards and guidelines is performed. As a result, key issues and best practices of the existing standards are identified. Based on this review, it is recommended to adopt the concepts of design flexibility and performance based design. Indeed, rigid standards, which do not really take into account safety and operational consequences of the design decisions and the need to balance opposing demands, might produce undesirable outcomes. Finally, research areas to fill the knowledge gaps are identified.

Key words: roundabouts, geometric design, sight distance, speed control, radius of deflection, entry path radius, deviation angle, safety, standards, guidelines.

INTRODUCTION

Intersections constitute only a small part of the overall highway system, yet intersection crashes constitute a significant portion of the total crashes. To reduce crashes and increase capacity, many intersections have recently been converted into roundabouts (Rodegerts et al., 2007a, 2010). The use of roundabouts improves intersection safety by eliminating or altering conflict types, reducing crash severity, and causing drivers to reduce speeds (Highways Agency, 2007a, 2007b; SETRA, 1998). Indeed, large and highly significant crash reductions were observed following conversion of signalized and stop-controlled intersections to roundabouts (Rodegerts et al., 2007b).

Despite the good safety record, roundabout performance strictly depends on the design features and several issues that significantly affect both crash frequency and severity have been observed at existing roundabouts (Montella, 2007, 2011; TNZ, 2000). Indeed, in several countries official design standards and/or guidelines for roundabouts have only been developed in the last few years. Since several inconsistencies in the roundabout design practices and standards are observed, in this paper a critical review of Australasian (Austroads, 2011; QDMR, 2006), European (CERTU, 1999; Italian Ministry of Infrastructures and Transports, 2006; Lombardia Region, 2006; SETRA, 1998; VSS, 1999), and US (Rodegerdts et al., 2010) roundabout guidelines and standards is presented. In Australasia, in France, and in the US there are technical guides which represent a suggested approach whereas Italian, Swiss, and UK documents set out design standards. Based on the critical review, key issues of the existing standards are identified, along with research areas to fill the knowledge gaps and recommendations to develop new standards.

ROUNDABOUTS CLASSIFICATION

Generally, roundabouts are classified in three basic categories according to the size and the number of lanes: mini-roundabouts, single-lane roundabouts, and multi-lane roundabouts.

Mini-Roundabouts

Mini-roundabouts are small roundabouts with a fully traversable central island. Mini-roundabouts are a valid design option on local roads (Table 1). Indeed, they are best suited to environments where speeds are low and environmental constraints would preclude the use of a larger roundabout. In some countries, speed requirements are specified. In the UK, roundabouts are allowed only on roads with operating speeds (V_{85}) below 56 km/h. In UK and France, maximum speed limit is respectively 48 and 50 km/h. In Australia and New Zealand (NZ), there are not any mini-roundabout design standards. In NZ, mini-roundabouts are generally being replaced with single-lane roundabouts, except when they are part of local traffic calming schemes.

UK is the only country requiring a minimum traffic to justify mini-roundabout installation: traffic flow on any arm should be over 500 vehicles per day (2-way AADT). Swiss standards require total AADT less than or equal to 15,000 v/d and the sum of entering and circulating traffic of each leg less than or equal to 1,200 v/h.

Maximum inscribed circle diameter (ICD, i.e. the diameter of the largest circle that can be fitted into the junction outline) ranges between 24 m (France) and 28 m (UK). The central island treatment is substantially different. In UK, US, and France the central island is fully traversable (flush or domed) whereas in Switzerland and Italy the island is non-traversable with a truck apron (traversable strip which allows to enhance the trajectories of trucks) when ICD is greater than or equal to 18 m. Swiss and Italian standard do not take into account the maneuvers of large vehicles which are not able to navigate mini-roundabouts with non-traversable central island.

Traffic islands may be provided to separate opposing streams of traffic and, if appropriate, to serve one or more of the following purposes: provision of adequate deflection of the path of vehicles approaching the mini-roundabout; increased conspicuity to drivers approaching the mini-roundabout; pedestrian use; and calming feature. Swiss and Italian standards do not give any advice about splitter islands whilst the other standards and guidelines recommend raised islands where possible. Splitter islands are raised, traversable, or flush depending on the size of the island and whether trucks will need to track over the top of the splitter island to navigate the intersection.

Single-Lane Roundabouts

This type of roundabout is characterized as having a single-lane entry at all legs and one circulatory lane. Single-lane roundabouts are allowed in all settings and all types of single-carriageway highways. Warrant criteria generally refer to relatively high traffic on minor road, relatively high left-turn volume from the major road, or safety issues. ICD ranges between 27 and 55 m.

Most countries require a truck apron around the non-traversable part of the central island when vehicle tracking indicates this is needed (Table 2).

Table 1. Mini-Roundabouts Design Characteristics

Parameter	**US**	**UK**	**France CERTU**	**Switzerland**	**Italy Lombardia Region**	**Italy National standard**
Highway type	Local	Local	Local	Local	Local	Local
Operating speed (V_{85})	≤ 50 km/h[a]	≤ 56 km/h	–	–	–	–
Speed limit	–	≤ 48 km/h	≤ 50 km/h	–	–	–
Minimum traffic	–	2-way AADT of all legs ≥ 500 v/d	–	–	–	–
Maximum traffic	AADT ≤ 15,000 v/d[b]	–	–	AADT ≤ 15,000 v/d $V_{ent}+V_{cir}$ ≤ 1,200 v/h	–	–
Inscribed Circle Diameter	≥ 13 m ≤ 27 m	≤ 28 m	≥ 15 m ≤ 24 m	≥ 14 m ≤ 26 m	≥ 14 m ≤ 26 m	≥ 14 m ≤ 25 m
Central island treatment	Fully traversable	Flush or slightly domed h ≤ 0.10 m d ≤ 4 m	Domed 0.10 ≤ h ≤ 0.15 m	ICD < 18 m Fully traversable ICD ≥ 18 m Non-traversable + truck apron	ICD < 18 m Fully traversable ICD ≥ 18 m Non-traversable + truck apron	ICD < 18 m Fully traversable ICD ≥ 18 m Non-traversable + truck apron
Splitter islands treatment	Raised, traversable, or flush[c]	Kerbed or flush	Kerbed or flush	–	–	–

[a] Common practice.
[b] Typical daily service volume on 4-leg roundabout below which may be expected to operate without requiring a detailed capacity analysis.
[c] Generally discouraged.

Only the Italian standard does not allow the truck apron, despite several aprons are installed on existing roundabouts. A traversable truck apron is typical for most roundabouts to accommodate large vehicles while minimizing other roundabout dimensions. A truck apron provides additional paved area to allow the over-tracking of articulated vehicles on the central island without compromising speed control for smaller vehicles. At the same time, the truck apron must be unattractive for use by passenger cars.

The width of the truck apron is defined based upon the swept path of the design vehicle. US guidelines recommend widths between 1.0 and 4.6 m and cross slope between 1 and 2% away from the central island. France and Italian regional standards recommend smaller widths (between 1.5 and 2.0 m) and greater cross slopes (between 4 and 6% away from the central island). Generally, small widths may be not enough to provide large vehicles tracking and high cross slopes might facilitate overturning. To discourage use by passenger vehicles, the outer edge of the apron is raised above the circulatory roadway surface. Height generally varies between 40 and 100 mm. The apron is constructed of a different material than the pavement to differentiate it from the circulatory roadway and to offer contrast against the circulating roadway that is perceptible by day as well as by night.

Splitter islands should be provided on all single-lane roundabouts. Landscaping and road furniture within splitter islands should not impede visibility of the roundabout or obstruct driver's sight lines, unless designers decide to reduce visibility with the aim of decreasing approach speeds. Splitter

Table 2. Single-Lane Roundabouts Design Characteristics

Parameter	Australia & New Zealand	US	UK	France SETRA	Switzerland	Italy Lombardia Region	Italy National standard
Highway type	All single carriageway	All single carriageway	All single carriageway	All single carriageway	All single carriageway	All single carriageway	All single carriageway
Operating speeds (V_{85})	≤ 80[a] km/h	–	–	–	–	–	Speed reducing measures
Inscribed Circle Diameter [m]	≥ 26 m ≤ 54[b] m	≥ 27 m ≤ 55 m	> 28 m ≤ 36 m	≥ 30[c] m ≤ 50 m	> 26 m ≤ 40 m	≥ 26 m ≤ 50 m	> 25 m ≤ 50[d] m
Central island treatment	Non-traversable + truck apron[e]	Non-traversable + truck apron[e]	Non-traversable + truck apron[e]	Non-traversable + truck apron[f]	Non-traversable + truck apron[e]	Non-traversable + truck apron[e]	Non-traversable
Truck apron	W=f(vehicle tracking) Cross slope = 2 – 2.5% H = 40 – 90 mm	W = 1.00 – 4.60 m Cross slope = 1 – 2% H = 50 – 100 mm	W=f(vehicle tracking)	W=1.50 – 2.00 m Cross slope = 4 – 6% H=30 mm	H=40 mm	W=1.50 – 2.00 m Cross slope = 4 – 6% H=30 mm	–
Splitter islands treatment	Area ≥ 40[g] m^2 L ≤ 60 m	L_{min} = 15 m L_{des} = 30 m L_{hspeed} ≥ 45 m	–	Construction triangle H=1/2 ICD B=1/8 ICD	W ≥ 3 m	W ≥ 3 m	–

[a] If V_{85} > 80 km/h consider speed reducing measures. [b] Greater ICD is allowed if there are more than 4 legs or if there is an high proportion of heavy vehicles. [c] On secondary roads with little heavy traffic, ICD between 24 and 30 m can be considered. [d] If ICD > 50 m the operational analysis is carried out considering the circulatory roadway as a weaving section. [e] Truck apron when vehicle tracking indicates this is required. [f] For ICD ≤ 30 m truck apron is mandatory, for ICD > 30 m truck apron is optional. [g] At least 10 m^2 for local streets.

islands should have a reasonably large area and should be long enough to give early warning to drivers that they are approaching an intersection and must slow down. The length of the splitter island may differ depending upon the approach speed. US guidelines recommend a minimum length equal to 15 m, a desirable length equal to 30 m, and a length of 45 m or more on higher speed roadways. In France, the splitter island shape is generated by a so-called construction triangle. The position of the construction triangle is derived from the axis of the leg and the edge of the circulating roadway. The height of the triangle is equal to ? of the ICD and the base is ? of the height. Swiss and Lombardia Region standards require a width not smaller than 3 m. The Italian national standard does not give any advice about the splitter islands.

Multi-Lane Roundabouts

Multi-lane roundabouts have at least one entry with two or more lanes (Table 3). ICD ranges between 30 and 100 m. In Italy, if ICD is greater than 50 m the operational analysis is carried out considering the circulatory roadway as a weaving section. This requirements makes almost impossible the use of roundabouts with ICD greater than 50 m, since the length of the circulatory roadway between any entry and the following exit is seldom enough to allow effective weaving.

Generally, multi-lane roundabouts are a design option on highways of several functional classes. Italy is the only country where roundabouts are not allowed on divided highways. Neverthless, the Italian standard is mandatory only for new roads and there are roundabouts in several existing divided highways. In Lombardia Region (Italy) there is a major flexibility since roundabouts are allowed on urban divided highways. The Swiss standard does not provide any specific advice for multi-lane roundabouts.

The number of lanes can vary from approach to approach. Likewise, the number of lanes within the circulatory roadway may vary depending upon the number of entering and exiting lanes. In general, the number of lanes provided at the roundabout should be the minimum needed for the existing and anticipated demand as determined by the operational analysis. Irrespective of capacity considerations it is generally important on arterial roads that lane continuity is available through roundabouts; that is, a roundabout serving a two-lane approach on a duplicated arterial road should have two entry lanes even if the calculations show that one-lane would have adequate capacity. The number of circulating lanes from any particular approach must be equal to or greater than the number of entry lanes on that approach. It is not essential to provide the same number of circulating lanes for the entire length of the circulating carriageway as long as the appropriate multi-lane exits are provided prior to reducing the number of circulating lanes. In France and in Italy, the circulating roadway is a single wide lane operating without lane separation markings.

In Australasia, UK, and US the number of exit lanes should equal the number of circulating lanes prior to the exit. In France, Switzerland, and Italy different rules apply. In France, exits are designed with one lane, except in the following cases: (a) $V_{exit} \geq 1,200$ pc/h; (b) $V_{exit} \geq 900$ pc/h and $V_{exit} \geq 3 \times V_{circ}$. In Italy and Swiss two lane exits are never allowed. It is worthwhile to observe that several of Italian existing roundabouts are designed with two exit lanes.

GEOMETRIC DESIGN

Several geometric design parameters are used in the international roundabout standards. In this section, an overview of some of the most important parameters is provided.

Central Island

Generally, the optimal alignment is when all the axes of the legs cross through the center of the roundabout. An offset of the approach alignment to the left of the roadway centerline (right in countries with left-hand traffic) allows for increased deflection and reduction of the impact to the right-side of the road but may create greater impacts to the left-side. An offset to the right (left in countries with left-hand traffic) is not commonly used because generates problems in achieving speed control objectives and makes the perception of the central island less conspicuous but may be appropriate in some instances, provided that speed requirements and other design considerations are met, to minimize impacts to the adjacent properties and/or to the landscape. Central islands should preferably be circular as changes in curvature of the circulating carriageway result in differential speeds and increase driver workload. However, elliptical, oblong, or other shapes may need to be used to suit unusual and/or constrained site conditions.

The central island presents an obstruction to traffic and therefore it should be recognizable at the required stopping sight distance. Most countries recommend deliberately obstructing forward visibility through the central island. Vegetation can be used to achieve this and to improve the aesthetic quality. In general, the purpose of landscaping is to differentiate the roundabout from the road

Table 3. Multi-Lane Roundabouts Design Characteristics

Parameter	Australia & New Zealand	US	UK	France SETRA	Switzerland	Italy Lombardia Region	Italy National standard
Highway type	Single and dual carriageways	Single and dual carriageways	Single and dual carriageways	All single carriageway	–	Single carriageway and urban dual carriageways	Only on single carriageway
Inscribed Circle Diameter [m]	≥ 34 m ≤ 62[a] m	≥ 46 m ≤ 91 m	> 36 m ≤ 100 m	≥ 30 m ≤ 50 m	–	≥ 50 m ≤ 70[b] m	> 25 m ≤ 50[c] m
Number of entry lanes	Lane continuity Minimum that achieves the desired capacity	Lane continuity Minimum that achieves the desired capacity	Lane continuity Minimum that achieves the desired capacity	2 in the approaches where 1 does not provide the desired capacity	–	1-2	1-2
Number of circulating lanes	≥ # entry lanes[d]	≥ # entry lanes[d]	≥ # entry lanes[d]	1 (no lane markings)	–	1-2	1 (no lane markings)
Number of exit lanes	≤ # circulating lanes	≤ # circulating lanes	≤ # circulating lanes	1 2 if: a) Vexit ≥ 1,200 pc/h b) Vexit ≥ 900 pc/h and 3? Vcirc	1	1[e]	1
Central island treatment	Non-traversable + truck apron[f]	Non-traversable + truck apron[f]	Non-traversable + truck apron[f]	Non-traversable + truck apron[f]	Non-traversable + truck apron[f]	Non-traversable + truck apron[f]	Non-traversable
Truck apron	W= f(vehicle tracking) Cross slope = 2 – 2.5% H = 40 – 90 mm	W = 1.00 – 4.60 m Cross slope = 1 – 2% H = 50 – 100 mm	W= f(vehicle tracking)	W = 1.50 – 2.00 m Cross slope = 4 – 6% H = 30 mm	H=40 mm	W = 1.50 – 2.00 m Cross slope = 4 – 6% H = 30 mm	–
Splitter islands treatment	Area ≥ 40 m^2 L • 60 m	L_{min}=15 m L_{des}=30 m L_{hspeed} ≥ 45 m	–	Construction triangle H = 1/2 ICD B = 1/8 ICD	W ≥ 3 m	W ≥ 3 m	–

[a] Greater ICD is allowed if there are more than 4 legs or if there is an high proportion of heavy vehicles. [b] Roundabouts with ICD > 70 m are classified as "Exceptional". [c] If ICD > 50 m the operational analysis is carried out considering the circulatory roadway as a weaving section. [d] Rule for each approach. It is not essential to provide the same number of circulating lanes for the entire length of the circulating carriageway. [e] Two lanes allowed if one lane provides less capacity than the exit volume. [f] Truck apron when vehicle tracking indicates this is required.

environment and the immediate surroundings. The landscaping of the central island can improve the perception of the roundabout from a distance, and block the perspective of the incoming user on the circulating roadway.

Speed Control

Achieving appropriate vehicular speeds through the roundabout is the most critical design objective. A well designed roundabout reduces the relative speeds between conflicting traffic flows by requiring vehicles to negotiate the roundabout along a curved path. Indeed, several studies showed that a geometric design allowing high speeds entering and negotiating a roundabout is associated with angle crashes due to failure to give way to vehicles already on the roundabout and rear-end crashes when vehicles brake suddenly (Arndt and Troutbeck, 2005; Montella, 2011; Turner et al., 2006). Main parameters used by standards to control speeds through the roundabout are the radius of deflection, the entry path radius, and the deviation angle.

Radius of Deflection

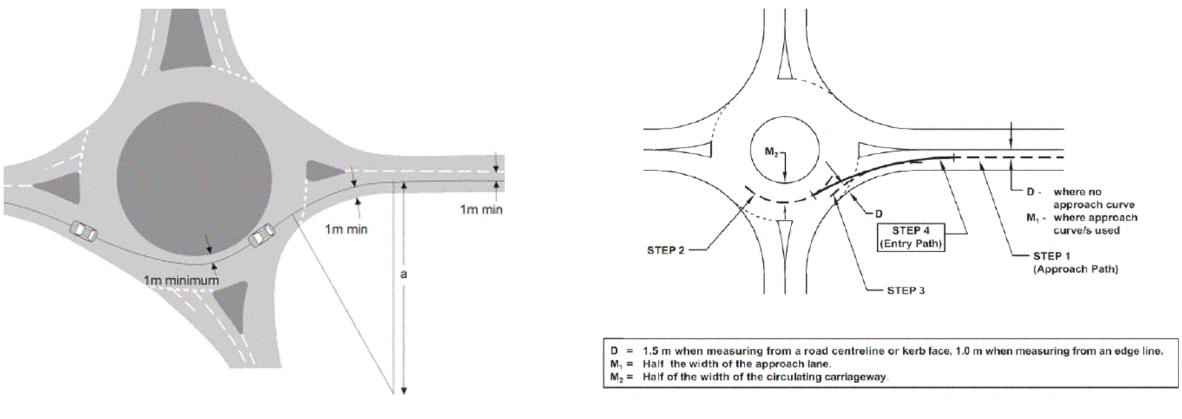
According to French standards (SETRA, 1998), a trajectory's deflection is the radius of the arc that passes at a 1.5 m distance away from the edge of the central island and at 2 m from the edges of the entry and exit lanes. The radius of such an arc should be less than 100 m. Recommended value is 30 m. Generally, the fastest path is the trajectory traced by two opposing arms; in particular circumstances, the fastest path is the right turn maneuver.

Entry Path Radius

Recently, there has been a move away from a focus on the deflection to controlling vehicle speeds through geometry of the roundabout entry. This has meant a focus on the entry radius and the maximum central circulating radius. The entry path radius is a measure of the deflection imposed on vehicles entering a roundabout. It is an important determinant of safety at roundabouts because it governs the speed of vehicles through the junction and whether drivers are likely to give way to circulating vehicles. To determine the entry path radius, the fastest path allowed by the geometry is drawn. This is the smoothest, flattest path that a vehicle can take through the entry, round the central island and through the exit (in the absence of other traffic).

In the UK, the entry path is assumed to be 2 m wide so that the vehicle following it would maintain a distance of at least one meter between its centerline and any kerb or edge marking. The path starts 50 m in advance of the give way line. The smallest radius of this path on entry that occurs as it bends before joining the circulatory carriageway is called the entry path radius (Figure 1a). Entry path radius should be measured over the smallest best fit circular curve over a distance of 25 m occurring along the approach entry path in the vicinity of the give way line, but not more than 50 m in advance of it. The entry path radius must be checked for all turning movements. It must not exceed 70 m at compact roundabouts in urban areas and 100 m at all other roundabout types.

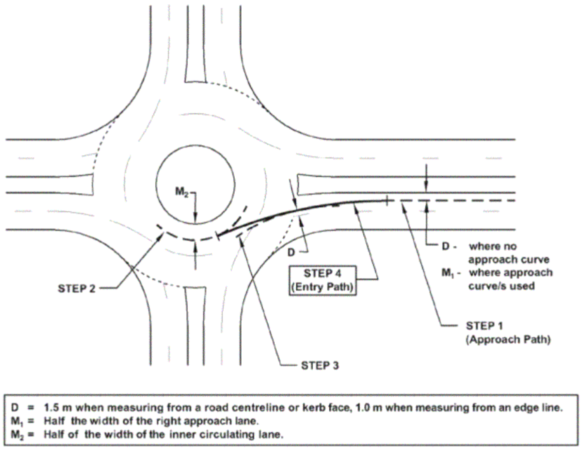
In Australasia (Austroads, 2011; QMDR, 2006), different procedures to construct the entry



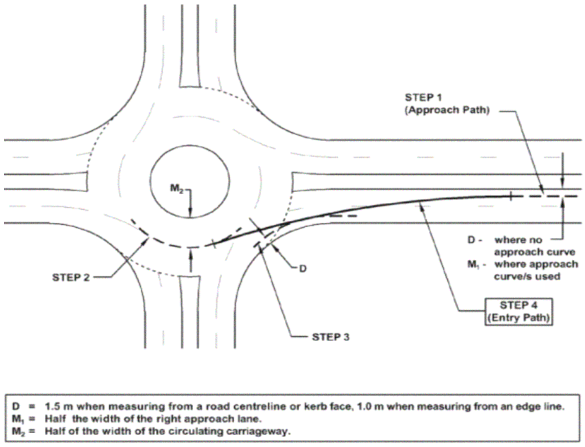
(a) Highways Agency, TD 16/07, figure 7-11

(b) Austroads, AGRD08/11, figure 4-6

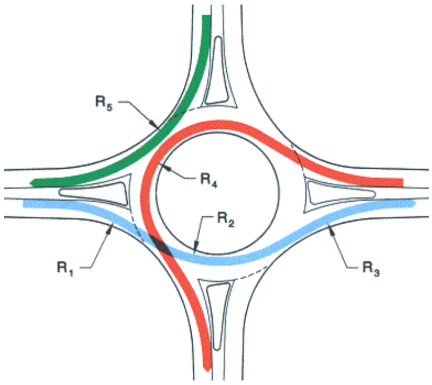
Figure 1. Procedures to construct the fastest path radius



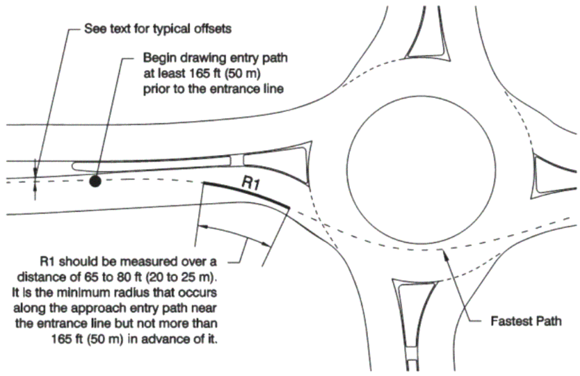
(c) Austroads, AGRD08/11, figure 4-7



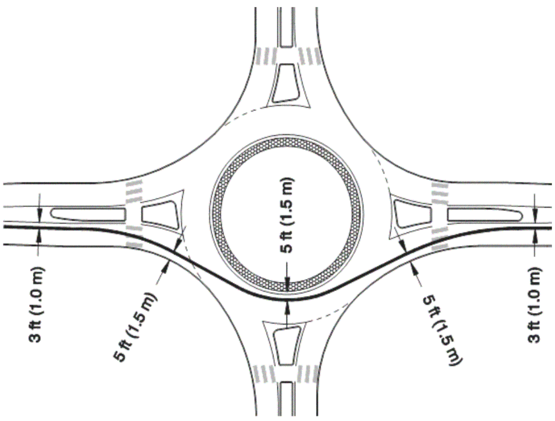
(d) Austroads, AGRD08/11, figure 4-8



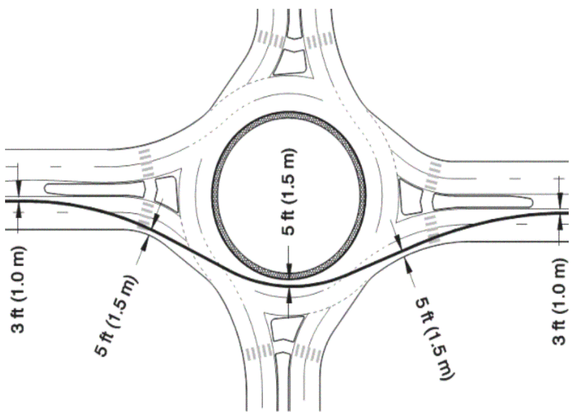
(e) TRB, NCHRP 672, exhibit 6-46



(f) TRB, NCHRP 672, exhibit 6-51



(g) TRB, NCHRP 672, exhibit 6-48



(h) TRB, NCHRP 672, exhibit 6-49

Figure 1. Procedures to construct the fastest path radius

path are defined for single-lane entries (Figure 1b), two-lane entries – staying in correct lane (Figure 1c), and two-lane entries – cutting across lanes (Figure 1d). For single-lane entries and two-lane entries – staying in correct lane, the maximum value of the entry path radius is 55 m. If the desired driver speed on the leg prior to the roundabout is less than 90 km/h, this value is increased (up to 100 m for V ? 40 km/h). For two-lane entries – cutting across lanes, the maximum radius is 1.5 times (1.9 for V ? 40 km/h) the actual entry path radius when staying in correct lane. We caution the reader that, differently from UK and US, in Australasia there is not specific research behind the speed vs. geometry parameters.

US guidelines (Rodegerdts et al., 2010) state that the fastest paths must be drawn for all approaches and all movements, including left-turn movements and right-turn movements. Five critical path radii must be checked for each approach (Figure 1e). R1, the entry path radius, is the minimum radius on the fastest through path prior to the entrance line. R2, the circulating path radius, is the minimum radius on the fastest through path around the central island. R3, the exit path radius, is the minimum radius on the fastest through path into the exit. R4, the left-turn path radius, is the minimum radius on the path of the conflicting left-turn movement. R5, the right-turn path radius, is the minimum radius on the fastest path of a right-turning vehicle. The R1 through R5 radii represent the vehicle centerline in its path through the roundabout. A vehicle is assumed to be 2 m wide and maintain a minimum clearance of 0.5 m from a roadway centerline or concrete curb and flush with a painted edge line (Figures 1f, 1g, and 1h). When drawing the path, a short length of tangent should be drawn between consecutive curves to account for the time it takes for a driver to turn the steering wheel. US guidelines do not directly provide a maximum value of the entry path radius, but recommend maximum entry design speed for mini-roundabouts (30 km/h), single-lane roundabouts (40 km/h), and multi-lane roundabouts (40-50 km/h) and provide radius-speed relationship. As a result, maximum recommended entry path radii are 30 m for mini-roundabouts, 55 m for single-lane roundabouts, and 85 m for multi-lane roundabouts. Furthermore, relative speeds between conflicting traffic streams and between consecutive geometric elements should be minimized such that the maximum speed differential between movements are no more than approximately 15 to 25 km/h.

Deviation Angle

The Swiss and the Italian standards require a deviation angle imposed by the central islands between two opposite legs greater than 45 degrees. The rationale is that if the vehicle flow is not deflected sufficiently from the straight direction of travel by the central island, this will lead to failures to give way, increased pass through speeds and underestimations of these speeds by conflicting parties. Experimental studies showed a correlation between smaller deviation angles and higher crash rates (Spacek, 2004). On the other hand, this value of the deviation angle is not attainable for small roundabouts, even for those roundabouts where speed control is attained through small entry path radius and radius of deflection.

Entry Width

Entry width is measured from the point where the entrance line intersects the left edge of traveled way to the right edge of the traveled way, along a line perpendicular to the right curb line (Figure 1). Entry width is a key factor affecting capacity, in conjunction with length and sharpness of flare. The entry width should be able to accommodate the swept path of the entering design vehicle. However, it is important that the entry is not any wider than necessary as excessive entry widths can make it difficult for designers to achieve adequate speed reduction at the entries to roundabouts, with detrimental safety consequences.

For single-lane entrances, typical entry widths range from 4.0 to 5.5 m; these are often flared from upstream approach widths. Care should be taken with entry widths greater than 5.5 m, as drivers may mistakenly interpret the wide entry to be two lanes when there is only one receiving circulatory lane. In Switzerland and Italy, smaller entry widths are required (3.0 - 3.5 m). Entry width required in Italy is smaller than the lane width of the rural collectors (3.75 m), thus requiring a lane narrowing in the roundabout approach. Smaller entry widths, in the range from 2.5 to 4.0 m, are required in mini-roundabouts.

In multi-lane roundabouts, the required entry width for any given design is dependent upon the number of lanes and design vehicle. Approach flaring may provide an effective means of increasing capacity without requiring as much right-of-way as a full lane addition. UK research suggests that length of flare affects capacity without a direct effect on safety (Rodegerdts et al., 2010). Widths for individual lanes at entry range from 3.0 to 4.6 m.

Entry Radius

The entry radius is an important factor in determining the operation of a roundabout because it affects both capacity and safety. Excessively large entry curb radii have a higher potential to produce faster entry speeds than desired. Care should also be taken to avoid entry radii that are too abrupt since these may lead to single-vehicle crashes. The outside line of the entry is commonly designed curvilinearly tangential to the outside edge of the circulatory roadway. Likewise, the projection of the inside edge of the entry roadway is commonly curvilinearly tangential to the central island. Some road authorities prefer that this projection passes through a point in the circulating roadway about 1.5 m from the central island in order to ensure that the vehicle tracks on the pavement rather than mounting the island.

At multi-lane roundabouts, the design of the entry curvature should balance the competing objectives of speed control and adequate alignment of the natural path. The use of small entry radii may produce low entry speeds but often leads to path overlap on the entry since tends to lead vehicles of the outside lane into the inside circulatory lane. Greater entry radii reduce the potential for path overlap. US guidelines recommend to use a compound curve or tangent along the outside curb. The design consists of an initial small-radius (20-35 m) entry curve set at least 6 m back from the edge of the circulatory road-way. A short section of a large-radius curve (> 45 m) or tangent is then provided between the entry curve and the circulatory roadway to align vehicles into the proper circulatory lane at the entrance line.

France and Switzerland require the smaller entry radii (8-15 m at smaller roundabouts) whereas countries which control vehicles speeds by the limitation of the entry path radius are more flexible and give chance of greater radii. Italian standard does not give any advice.

Entry Angle

The entry angle is the conflict angle between the entering and the circulating traffic. In general, too low entry angles produce poor angles of visibility to the left (right in countries with left-hand traffic), requiring drivers to strain to look over their shoulders, and may encourage merging behavior similar to freeway on-ramps. Meanwhile, too high entry angles may not provide enough positive alignment to discourage wrong-way movements, reduce capacity and may produce excessive entry deflection which can lead to sharp braking at entries accompanied by rear-end crashes. Swiss standard requires entry angles between 70 and 90 degrees, thus producing perpendicular entries, whilst the UK standard requires angles between 20 and 60 degrees (in these countries the definition of entry angle is slightly different).

Circulatory Roadway Width

The required width of the circulatory roadway is determined from the number of entering lanes and the turning requirements of the design vehicle. In general, the circulating width should be at least as wide as the maximum entry width and up to 120% of the maximum entry width (Highways Agency, 2007b; Rodegerdts et al., 2010).

For single-lane roundabouts, the circulatory roadway width usually remains constant throughout the roundabout. Typical circulatory roadway widths range from 5 to 7 m. Care should be taken to avoid making the circulatory roadway width too wide within a single-lane roundabout because drivers may think that two vehicles are allowed to circulate side-by-side. The circulatory roadway width should accommodate all but the largest vehicle (in US only cars and buses). A truck apron will often need to be provided within the central island to accommodate the largest design vehicles. Usually, the left-turn (right-turn in countries with left-hand traffic) movement is the critical path for determining circulatory roadway width. At mini-roundabouts, larger circulatory widths are needed (typically from 7 to 8 m).

At multi-lane roundabouts, the circulatory roadway width may be variable depending upon the number of lanes and the design vehicle turning requirements. A constant width is not required throughout the entire circulatory roadway, and it is desirable to provide only the minimum width necessary to serve the required lane configurations within that specific portion of the roundabout. A common combination is two entering and exiting lanes along the major roadway, but only single entering and exiting lanes on the minor street.

Multilane circulatory roadway lane widths typically range from 3.5 to 4.9 m per lane. In France and in Italy, the circulating roadway is a single wider lane operating without lane markings.

Exit Width

The exit width is the width of the carriageway on the exit and is measured in a similar manner to the entry width. Exit lane widths need to be checked for vehicle swept paths to ensure that the design vehicle is properly accommodated. For single-lane exits, typical widths range from 4.0 to 7.5 m. Smaller exit widths, in the range from 2.5 to 4.5 m, are required in mini-roundabouts. For double-lane exits, typical widths range from 7.0 to 11.0 m.

Exit Radius

In general, standards and guidelines require to use relatively large radius so that it is comfortable for drivers to exit roundabouts. In urban areas, this is balanced by the need to maintain slow speeds through the pedestrian crossing on exit. The exit right edge is commonly designed to be curvilinearly tangential to the outside edge of the circulatory roadway. Likewise, the projection of the inside edge of the exit roadway is commonly curvilinearly tangential to the central island.

RESEARCH AREAS TO FILL THE KNOWLEDGE GAPS

All the standards and guidelines agree that achieving appropriate vehicular speeds through the roundabout is the most critical design objective. However, the parameters and threshold values used to achieve the appropriate speed controls are different and research does not provide enough quantitative estimates of the safety effects of the changes in the speed control parameters. Sound research might provide meaningful insight to improve geometric design standards and guide towards the optimal balance between the conflicting design parameters.

Safety performance functions which take into account the parameters used by the standards would be a great research outcome. Maycock and Hall (1984) found that roundabouts with no deflection had crash rates about 8.5 times those with maximum deflection. Turner et al. (2006) found that free speeds of vehicles travelling through the roundabouts at the limit line are positively related to entering-circulating crashes. Rodegerdts et al. (2010) found that entry radius, entry width, approach half width, inscribed circle diameter, and circulating width are positively correlated with crashes whereas angle to the next leg has a negative impact on crashes. Recently, Chen et al. (2013) have found that approach average speed (average value of measured entry, upstream circulating and upstream exiting speeds) is positively correlated with crashes. These studies show that research can provide meaningful insights to support design decisions, even if more efforts and calibration of the models in different local conditions are needed.

Crash studies might be effectively integrated by traffic conflict analyses. Traffic conflicts are surrogate safety measures which address several shortcomings associated with crash data such as the scarcity of collisions, the need for long observation times and the questionable quality of crash data. Traffic conflicts are more frequent than crashes and are of marginal social cost. Traditional on-site methods for collecting traffic conflict data are labour-intensive, time consuming, and costly and suffer from reliability issues. Video sensors are an alternative data collection procedure, solving many issues in the manual data collection and providing a more reliable and efficient way to capture, store and analyze traffic information. Automated computer vision-based video analysis for analyzing traffic conflicts have been developed and validated (Sayed et al., 2013). Study of traffic conflicts on roundabouts with several geometric configurations, coupled with the analysis of the driving speed behaviour, might provide fundamentals insight to understand the effect of speed control design parameters on the failure mechanism that leads to road crashes.

Investigation of drivers' responses to changes in roundabout geometric design is a complex task because it is difficult to exert control over all design parameters (e.g., inscribed circle diameter, entry width, entry path radius, radius of deflection, and sight distance) and confounding factors such as the number or type of vehicles involved or the demographics of the driving population. High fidelity driving simulation technology can provide a cost-effective alternative in the evaluation of driving behaviour, without posing any risk to the drivers. Indeed, driving simulators have a potential to explain interaction between drivers and geometric design, even though the use of driving simulators has some possible shortcomings including physical limitations, realism, and validity (Montella et al., 2010, 2011).

Sometimes neither a single-lane or multi-lane roundabout can cope with the volumes of the different traffic flows at an intersection. In these cases a signalized multi-lane roundabout might be a satisfying alternative to an expensive and space consuming grade separated intersection. However, little is known about the performance of signalized roundabouts, both related to traffic flow and to traffic safety, although many have been built with different sizes and shapes (Ministry of Transport, Public Works and Water management, 2009). Research on operational and safety performance of signalized roundabouts, both by field studies and by traffic microsimulation, might provide substantial benefits.

Last but not least, a research area which deserves significant efforts relates to the safety of pedestrians and bicyclists in relation to the different facilities.

CONCLUSIONS

Geometric design criteria are of fundamental importance to achieve the best performance of roundabouts in terms of both capacity and safety. A review of the Australasian, European Union and United States standards and guidelines showed that the interaction of the roundabout geometric elements is more important than their individual impacts. As a consequence, it is recommended to adopt the concepts of design flexibility and performance based design. Indeed, rigid standards, which do not really take into account safety and operational consequences of the design decisions and the need to balance opposing demands, might produce undesirable outcomes.

Finally, it is worthwhile to highlight the need for further research on the relationships between roundabout geometric design criteria, drivers' behavior and safety. At this aim, directions for research may be based on calibration of the safety performance functions incorporating geometric design parameters, automated video analysis for analyzing traffic conflicts, and use of high fidelity driving simulators to test the effects on drivers' behaviour of the interaction of several geometric parameters.

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