Understanding Safety-Related Issues for Pedestrians at Modern Roundabouts

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Received: February 3, 2012 Accepted: February 28, 2012 Published: April 1, 2012
doi:10.5539/jsd.v5n4p23 URL: http://dx.doi.org/10.5539/jsd.v5n4p23

Abstract

This paper examines the safety-related issues for pedestrians at modern roundabouts. For this purpose findings of research studies documented in the scientific literature and best practices have been examined trying to focus on roundabout installations by a pedestrians safety perspective. Whereas one of the main reasons for which roundabouts are built is related to safety benefits, roundabout design features and implications in road casualties have been commented first to evaluate the influence of roundabouts on pedestrian safety and then to identify design elements that have such a high potential for traffic safety. At last, measures and treatments that can be taken in the roundabouts design for addressing the needs of pedestrians are also presented by type, according to their effects on safety; this is proposed with the intention to recommend solutions to improve the sharing of road space between vehicles and non-motorized traffic and to assist planners and designers in doing safe roads for vulnerable users.

Keywords: Pedestrian facilities, Roundabouts, Road safety, Road design

1. An Introduction on Safety-Related Issues at Modern Roundabouts

Sustainable design practices are now required increasingly to ensure that roads have a recognizable design and predictable traffic situations where users know what they should do and what they can expect from other users. Promoting a pedestrian-friendly environment involves trade-offs among different users needs, such as the integration between motorized traffic and pedestrians where speeds are low and the separation where speeds are too high. In this view modern roundabouts represent a very safe design solution compared with other conventional intersections, both for effects on speeds and for effects on conflicts between road users. In order to support safe pedestrian activities, this consideration should be taken into account in the formulation and implementation of pedestrian master plans of which many communities and local agencies are equipping themselves in the construction of new road infrastructures and the upgrading of existing facilities. Moreover, the sustainability of road facilities is a priority for road planners and traffic engineers, because it is directly related to the prevention and then to the reduction of road crashes. More specifically road intersections are the elements of the road network characterized by a considerable potential for crash reduction after the installation of schemes likely to promote the improvement in safety performances. The geometric design of a new roundabout, as well as the conversion of existing intersections into roundabouts, can produce a significant reduction both in injury and in property-damage crashes, as long as road administrators are able to assess preventively the unsafety situations joined to traffic conditions modified by new installations.

1.1 Considerations on Modern Roundabouts

Modern roundabouts are circular intersections where vehicles circulate counterclockwise around a central island and in which entering vehicles must give the right-of-way to circulating vehicles, stopping where expected at the

edge of the circulatory roadway until a gap in the circulating traffic flow becomes available. Rodegerdts et al. (2010) have recently described in a comprehensive manner key roundabout features. In this regard, Figure 1 shows examples of typical (single-lane and two-lane) roundabouts, as well as individual geometric elements for the design of a single-lane entry/exit. The same figure depicts splitter islands at approaches to separate entering and exiting lanes; they also provide a refuge for pedestrians which allows them to cross the street in two stages (Wadhwa, 2003). It should be noted that many of these design principles can also be applied to design of multilane roundabouts, whose complexities require care in the study of the interaction among different design elements, as well as in the verification of their compatibility to meet design purposes (Rodegerdts et al., 2010). Within the category of roundabouts great variations in design patterns are possible with regard to size of the inscribed circle diameter (or otherwise said outer diameter), number of lanes, central island radius, curvature of entry/exit lanes, lane width, and so on. A recent and interesting, albeit brief, classification of roundabouts can be found in the 2nd edition of Roundabouts: An Informational Guide (NCHRP Report 672, 2010); only for informative purposes, some minimum desirable values of fundamental design elements for each roundabout category (mini, compact and conventional), as reported by the Italian standards for road intersections (2006), are summarized in Table 1. Without expecting to be exhaustive, Table 2 summarizes some of the well-known roundabout design guidelines and manuals used in the world.

The overall examination of crash reports and crash types that have been experienced for some time in various European Countries (Guichet, 1980; Maycock & Hall, 1984; Brilon & Stuwe, 1993; Schoon & van Minnen, 1994), in Australia (Arndt, 1998), and in the last few years in the United States (Rodegerdts et al., 2007), allows to assert that the main benefit from roundabout installations is the improvement in safety performances compared with other intersection control modes. According to roundabout practices and guidelines (see Table 2), this can be attributable to specific design details and features that are common to all types of roundabouts, such as the curvature of the entry path exerting physical guidance and providing adequate speed reduction to entering vehicles, the large deflection on approach minimizing speeds inside the circle, the installation of the central island reducing the number of potential conflict points from 32 to 8 at single-lane roundabouts, the separation of the various movements by the splitter islands at approaches. Roundabouts may represent a valuable alternative to two-way-stop-controlled intersections where heavy left turns from the major street occur, or even where the minor street volume is low; they may also be an effective alternative to signalized intersections because they allow an overall reduction in vehicle speeds, eliminate red-light running, and remove potentially dangerous conflicts like right-angle collisions or frontal collisions (Rodegerdts et al. 2010). Despite the roundabouts are able to improve some safety problems compared to other at grade intersections, however regulated, taking into account size, the context of installation and site constraints, not all roundabouts have the same safety performance. From a safety point of view, small- and medium-capacity roundabouts perform better than large or multilane roundabouts (Maycock & Hall, 1984; Alphand et al., 1991; Rodegerdts et al., 2007). Single-lane roundabouts, indeed, offer greater safety benefits than multilane roundabouts due to fewer points of conflict; at roundabouts with multiple approach lanes, an additional conflict is added with each additional lane that a pedestrian must cross (Rodegerdts et al., 2010). Among the high-capacity patterns of roundabouts, the design choice may fall on two-lane roundabouts or on turbo-roundabouts with more recent design. The first type have the disadvantage of a higher driving speed through the circulatory carriageway than single-lane schemes; they also reintroduce the possibility of lane changing on the roundabout, raising the crash risk. Adequate evaluation of safety performances has not been available yet for turbo-roundabouts, due to only a few installations are actually operating (Fortuijn, 2009). It has to be said that some countries have a small overall number of intersections that were converted to roundabouts, because conversions in urban areas are often conditioned by physical and topographical constraints, leading to compromise solutions for one or more geometric features of the intersection. These atypical schemes maintain traffic along the circulatory roadway, but for some movements operate as stop-controlled intersections; thus results of safety evaluations at these installations cannot be a reference for geometric design. Despite results of the crash analysis showed some features of crash phenomenon specific for the examined not-conforming roundabouts, Granà (2007) noted that vulnerable users (pedestrians and two-wheelers) can be particularly exposed to crash risk, both in absolute terms and as regards literature informations (Alphand et al., 1991). It must be said, however, that capacity constraints and limited rights-of-way may exclude the possibility of converting many busy urban intersections to roundabouts (Retting et al., 2001). Anyhow, a properly designed roundabout, installed at locations appropriate and compatible with physical conditions of the context, has also the potential to generate advantages in terms of traffic delays and capacity and with regard to environmental, economic and esthetic aspects.

1.2 Crash Data and Statistics at Roundabouts

Crash and injury statistics indicate a significant reduction in all and injury crashes as a result of the installation of roundabouts due to the elimination of some vehicular conflict points and to lower entry speeds of vehicles by the features of the design both for urban and for rural settings (Maycock & Hall, 1984; Alphand et al., 1991; Arndt, 1998; Flannery & Datta, 1996; Guichet, 1997; Persaud et al., 2001; Retting et al., 2001; De Brabander et al., 2005; Rodegerdts et al., 2007; Isebrands, 2009). Where roundabouts replaced intersections under stop or traffic signal control, large reductions were found in injury crashes (76 percent), especially those involving fatal injuries (90 per cent); however, crash reductions are most pronounced for cars, less pronounced for other modes (Retting et al., 2001). Figure 2 shows for illustrative purposes only the comparison of crashes reductions observed in various countries when stop-controlled and signalized intersections were converted to roundabouts (Rodegerdts et al., 2010); furthermore, Figure 3 shows percentages of major crash types at roundabouts reported in different countries where single and multilane roundabouts have been in operation by time; the same figure illustrates the percentages of the main crash types that have taken place at US roundabouts (Rodegerdts et al., 2007). Further distinction can be made between entering–circulating and exiting–circulating crashes at single-lane and multilane roundabouts as reported by Mandavilli et al. (2009): between these two types of crashes, the percentage of entering–circulating crashes was predominat (13 per cent of all crashes at single-lane roundabouts and 17 per cent at multilane roundabouts) compared to exiting–circulating crashes (4 per cent of all crashes only at multilane roundabouts). A summary of safety studies taken to evaluate crash reductions at roundabouts (also with regard to pedestrians) compared to other intersection types is shown in Table 3.

International experience shows that alignment of approaches can play a decisive role in the occurrence of certain crash types: an entry tangential to the circular roadway decreases both the opportunity to deflect entering vehicles into a proper entry path and to reduce entry speeds, resulting in more loss-of control and entering-circulating crashes (entering drivers will be less inclined to yield); tangential exit can increase vehicles exit speeds and the risk for pedestrians on crosswalks (Rodegerdts et al., 2007). According to Weber (2007), instead, an almost centered alignment at the roundabout can generate rear-end and loss of control crashes in relation to the need to make abrupt braking. In order to ensure consistent speeds for circulating and entering vehicles, as well as decreasing speed differentials with other road users, trade-off considerations can interest size and position of splitter islands, entry approach alignment and angle between legs without compromising sight distances and the opportunity to accommodate trucks due to severe curvature of the entry path. Construction of the fastest vehicle path at a roundabout is illustrated in Figure 4, which also includes information on the deflection curve radii at roundabouts for various entry design speeds.

Several studies have been carried out since 1980s with the purpose to develop support tool for planners and engineers in designing safer roundabouts and in optimizing accessibility issues through design features (Maycock & Hall, 1984; Arndt, 1998; SETRA, 1988; Brüde & Larsson, 2000; Rodegerdts et al., 2007; Daniels et al., 2010). A comprehensive set of various roundabout design elements having a positive (or not) effect on safety and operations has been summarized in Table 4; Table 5 reports only effects of design elements on safety by crash category. In order to understand the relationship between roundabout design features and crash frequency, the use of safety models can provide help in quantifying the safety implications of design choices and in determining the effectiveness of roundabout treatments in road constructions. A review of safety prediction models that can be done through intersection-level and approach-level analyses is reported by Rodegerdts et al. (2007). The intersection level models have been developed for total and injury collisions; the approach-level models have been developed for all severities combined for entering-circulating, exiting-circulating and approaching collision types. According to Rodegerdts et al. (2010) these models are likely to be included in the second edition of Highway Safety Manual.

Starting from these considerations, in the next section the international experiences with roundabouts and pedestrians is summarized trying to focus on possible effects of roundabouts on pedestrian safety. Moreover, by deepening of current design practices for pedestrians at roundabouts, design elements targeted at promoting pedestrian safety at these intersections will be discussed later.

2. The Influence of Roundabout Facilities on Pedestrian Safety

In a sustainable vision, measures designed to improve opportunities of urban mobility, to achieve the homogenous use of roads and to maintain safe and accessible transport infrastructures should be based on the principle of sharing the road safely between vehicles and vulnerable users. The sustainable mobility is currently a goal to be pursued, but it can also be a factor of social qualification allowing processes that could lead to the reduction in vehicular congestion and to the increase of road safety (SWOV, 2006). If integration between cars

and non-motorized traffic is not encouraged by comprehensive pedestrian safety strategies and programs, it can be difficult for vehicles and pedestrians to safely share road facilities. This may be of particular interest to urban intersections where vehicle-pedestrian conflicts represent a frequently recurring situation even with low pedestrian volumes. Despite the statistics tell us that the road crashes and fatalities over time have decreased, they are still a concern for communities and all stakeholders. In support of the above said, crash frequencies now available from official sources (US and European) are reported in Tables 6 and 7. US data show that for years 2000-2009 pedestrian fatalities as a proportion of all fatalities are on average equal to 11.4; in 2009 only pedestrian fatalities are on average equal to 11 per day with an injured every 9 minutes (see Table 6). Despite the proportion of fatalities who were pedestrians differs widely across Europe, data report that pedestrian fatalities in the EU-23 fell about by 35 per cent between 2000 and 2009; in 2009 only casualties in pedestrian crashes are approximately equal to 18 per day (see Table 7). It can be observed globally a decrease in pedestrian fatalities, but the percentage on total is growing, even with reference to the high percentage of pedestrian fatalities inside urban area (see Table 7). Crashes are concentrated at intersections where the potential for vehicle–vehicle and vehicle–pedestrian conflicts is high; but it is also true that some forms of intersection control are more effective than others in reducing conflicts (Ewing & Dumbaugh, 2009). Table 8 reports US pedestrian fatalities by location (i.e. intersection and non intersection only): pedestrian fatalities as a proportion of all fatalities in intersections is approximately equal to 22 per cent. According to US data in 2009 only, 21 per cent of pedestrians killed was due to improper crossing of roadway or intersection and 16 per cent due to failure in yielding right-of-way (see Query FARS data).

2.1 Discussing on Safety Benefits for Pedestrians at Roundabouts

As introduced in the previous section, modern roundabouts promote safety better than traditional intersections with stop signs or traffic signals due to their effects on speeds and to the reduction in the number of potential conflicts between high-speeding vehicles (or right-turning vehicles or left-turning vehicles) and pedestrians crossing the street; even where crash frequencies are comparable to other intersections, crash severity is less (Maycock & Hall, 1984; Schoon & Minnen, 1993, 1994; Retting et al., 2001; Daniels & Wets, 2005; Rodegerdts et al., 2010). Conversions of intersections into roundabouts have already been foreseen by several road authorities around the world within geometric treatments to reduce various pedestrian crash types; but concerns on pedestrian safety should be raised before the roundabout construction (Jacquemart, 1998; Zegeer & Bushell, 2012). Although international experience also based on injury statistics confirm that pedestrians safety at roundabouts seems to be high, Persaud et al. (2001) indicated that no significant conclusions can be drawn on this trend, at least until the experience will be limited by availability of pedestrian crash data to be processed such as to ensure sufficient stability in the results. With respect to pedestrians safety, other European studies provided interesting results to which, however, reference can be made. As mentioned by Robinson et al. (2000), Brilon (1996) analyzed in Sicherheit von Kreisverkehrsplatzen (unpublished paper) before-and-after crash conditions at 34 roundabouts (including single-lane roundabouts with D_o=30 m, two intersections previously signalized and the others stop-controlled) and observed that pedestrian crashes decreased from 8 to 2. Brüde and Larsson (2000) examined vehicle-pedestrian crash data from 72 roundabouts in Sweden and showed a reduction of 78 percent in pedestrian injuries at single-lane compared to stop signs or traffic signals intersections; multi-lane roundabouts also resulted safe enough. Large variance in safety performances at roundabouts for some user groups was highlighted by other studies such as Schoon & van Minnen (1993) and Daniels et al. (2008).

Daniels et al. (2010) argued that the variation in crashes can be explained by reading the structural differences between locations and it is attributable to the traffic exposure; some users (mainly bicyclists and moped riders in absence of cycle path) are more frequently than expected involved in crashes at roundabouts. However, above authors cannot express similar considerations with regard to pedestrian safety. In any case it is possible to say that the slower traffic speeds through intersections, the reduction in the number of conflicts and the minimization in the conflict area between vehicles and pedestrians are three reasons generally cited to explain safety benefits for pedestrians at roundabouts (Jacquemart, 1998).

According to Furtado (2004) and Weber (2007) roundabouts safety benefits for pedestrians are: i) vehicular speeds are reduced and then injuries can occur with less chance and severity; ii) pedestrians in the crosswalk are more easily seen by drivers; iii) splitter islands make the crossing distances shorter and simplify vehicle-pedestrian conflicts, allowing pedestrians to observe one vehicular direction at a time; iv) the absence of an exchange of the right-of-way priority by the traffic signals makes perceived risks higher than real risks; v) shorter delays for pedestrians than signalized intersections. According to Jacquemart et al. (1998) roundabouts can be perceived as unsafe by pedestrians compared to signalized intersections, but crash risks from left-turning

vehicles crossing the intersection during the same phase as the pedestrian crossing fail (Habib, 1990); moreover, long waiting times characterize pedestrian crossing movements at signalized intersections and often motivate pedestrians to walk across a road where it is not allowed or without taking care to avoid the traffic (Furtado, 2004). Despite the benefits, disvantages for pedestrians are attributable to the following: i) entering vehicles do not always respect the stop making uncertain pedestrians in the crosswalk; ii) difficulties for pedestrians to assess gaps in traffic flows; iii) the position of crossings from the yield line can increase travel distances for pedestrians; iv) there are serious issues of accommodation and access for pedestrians with disabilities. Even if the crash data have not yet revealed a significant relationship between pedestrian crashes and roundabout geometry (Maycock & Hall, 1984), the results of a study conducted by Tumber (1997) for the evaluation of pedestrian crashes showed that 45 percent of crashes involving pedestrians occurred at roundabout entries and 27 percent at exits (while the remaining pedestrian crashes were distributed on the circulating roadway (17 percent), on the footpath (3 percent), and at other locations (8 percent); pedestrian crashes occurred where pedestrians were most frequent and pedestrian injuries were less severe at roundabouts than at other intersection control devices. According to Wegman and Aarts (2006) the correct approach speed is up to 30 km/h; at this speed all crashes between vehicles and pedestrians end without fatal injuries.

Empirical crash research has allowed to define roundabout auditing principles (Lenters, 2005) and some recommendations have been proposed and summarized: i) ensure the vehicle speed reduction prior to pedestrian crossings and mutual visibility between pedestrians and vehicles; ii) implement measures to conduct pedestrians to crosswalks, discouraging inappropriate movements and ensure proper location and alignment for splitter island crossings; iii) place the pedestrian crossing at a suitable distance from the yield line to simplify conflicts, separating pedestrians from the vehicle-vehicle conflicts, and to facilitate access to users with disabilities (Tumber, 1997). Geometric treatments and engineering modifications to the built environment were found to be important to reduce risks of pedestrian injuries and fatalities (CETUR, 1988). It is not clear, or there is no international consensus on the contribution of each geometric element on safety and operational performances; however, the opportunity to combine certain basic principles within the roundabout design has already been shared (Rodegerdts et al., 2007).

The above considerations introduce the review of practices and implications in roundabout design aimed at identifying engineering measures and design elements that should be adequate to amplify the potential effectiveness of the scheme in terms of safety for pedestrians; this will be shown in the following section.

3. Current Design Practices for Pedestrians at Roundabouts

From a road safety perspective, two approaches are usually taken to provide safe places for crossing the road and more generally to improve pedestrian safety. The first approach is soft type based on the promotion of appropriate behaviors by persuasion of the individual user to behave in a proper way when using road facilities (e.g. when crossing the road). The second approach is hard type and it aims to identify and implement measures that result in external constraints on road users and make road space also more conducive to pedestrian traffic activities. Road safety educational programs, as well as information and awareness campaigns by advertising, can be traced back to the first approach. These measures are in most cases aimed at educating young people, but mostly prefer drivers that, when driving, may be less inclined to consider the needs of pedestrians. There are some difficulties in evaluating the effectiveness of these interventions in relation to other aspects such as changes in the road environment or implementations of engineering measures (Sentinella, 2004). In general interventions to promote safe driver behaviors are likely to contribute to pedestrian safety whereas best driving behaviors can help to reduce pedestrian-vehicle conflicts (Martin, 2006). Traffic enforcement measures and road engineering interventions belong instead to the second approach; these measures can be regarded as aimed at the reduction of the number of pedestrians crossing away from crossing points warranted where most collisions occur. According to Retting et al. (2003) traffic engineering measures can be designed to manage vehicle speeds, to separate pedestrians and vehicles by time and space and to increase the visibility of pedestrians. Figure 5 gives a summary of measures by type that in planning and designing roads can be targeted at improving pedestrian safety. It should be added that traffic safety engineering can use now a large body of knowledge, in the form of design standards, guidelines and manuals to shape the road layout with a view to prevent road injuries and to encourage better uses of roads, as well as to minimize the number of vehicle-pedestrian collisions. However studies and research findings here examined suggest that sharing of road space between vehicles and pedestrians can be difficult when safety-awareness in planning roads is lacking, or when road geometric design and built environment ascribe low priority to pedestrians (Retting et al., 2003). An interesting overview of pedestrian strategies with reference to countermeasures to apply for reducing pedestrian crashes is reported by Zegeer and Bushell (2012) to which reference is made.

It is widely accepted that among different types of engineering treatments targeted to attain speed reductions, roundabout installations on the whole represent a very effective measure; at roundabouts, indeed, the angle of impact is smaller and in case of collisions crash consequences result less severe. Given the aim of this review (which is to examine the design features of modern roundabouts in a pedestrians safety perspective), the key operational and design elements that must be applied to promote pedestrian safety at roundabouts have been classified by types of engineering measures as reported in Table 9. It must be said that to meet overall safety and operational targets within engineering measures the interaction between elements of the roundabout geometric layout and the mutual compatibility between them are more important than the individual components taken individually. Road safety engineering measures and interventions would appear to have great potential on the basis of which they can give an important contribution to injury prevention and to mitigation; but further study is required to establish engineering interventions environmentally appropriate to local circumstances, and to test their actual effectiveness in increasing pedestrians safety, also with reference to specific treatments and provisions to be taken for the site under evaluation. However, considering the limited availability of resources compared to the large number of roads to be built and/or upgraded, particularly in developing countries, these measures with the greatest potential for crash reduction should have priority. Many studies on safety effectiveness of road engineering measures have experienced limitations in relation to the method adopted; it is the case of failure to account for regression to the mean resulting in overestimation of the effects of an intervention when high-crash locations are selected in order to achieve safety improvements (Retting et al., 2003). Some observational road safety studies have already been considered pedestrian–motor vehicle conflicts to evaluate road countermeasures; traffic conflict studies, indeed, can provide an indirect measurement of safety. Research into the validity of the traffic conflicts technique based on empirical evidence was carried out by Hauer and Garder (1986). Another issue of great importance is how roundabouts can be safe places for pedestrians with visual disabilities (Wadhwa, 2003). Further study and researches to identify what design features and treatments may be appropriate for accommodating pedestrians with cognitive disabilities and with reduced mobility at modern roundabouts are still necessary.

4. Conclusions

According to the principles of sustainable outlined in Advancing Sustainable Safety edited by SWOV (2006), pedestrians and vehicles are required to safely share the road; in this case the need that roads have a recognizable design and predictable traffic situations where users know what they should do and what they can expect from other users, should be even more deeply felt. Promoting a pedestrian-friendly environment with spaces and streets able to offer adequate conditions of safety and accessibility, involves trade-offs which concern integration between motorized traffic and pedestrians (where speeds are low) and the separation (where speeds are high) with application of targeted speed reductions where pedestrians cross motorized traffic at high flow sites. Within traffic engineering measures targeted at handling road users needs in a sustainable safety manner, modern roundabouts represent a very safe solution compared with other types of intersections both for effects on speeds and for effects on conflicts between users; this should be taken into account in the formulation and implementation of pedestrian master plans of which many municipalities and local agencies are equipping themselves to construct new road infrastructures and to upgrade existing facilities. To produce a better understanding of the size and potential impacts for the roundabout alternative, design considerations should be evaluated already at a planning level and in the phase of the detailed design, emphasizing the elements most favorable to the sharing and to equally distributed use of road spaces from a pedestrians safety perspective.

In this paper research findings of studies documented in the scientific literature and best practices have been examined trying to focus on the safety-related issues for pedestrians at modern roundabouts. To assist planners and designers in doing safe roundabouts, measures and treatments that can be taken in the roundabouts design for safely addressing the needs of pedestrians are also presented by type according to the effects on safety, with the intention to recommend useful solutions to improve the sharing of road spaces between vehicles and non-motorized traffic. The reader is advised that this research cannot be considered exhaustive, but it provides an overview of the current state of practices and implications in the roundabout design aimed at identifying engineering measures and design elements that should be adequate to amplify the potential effectiveness of the scheme in terms of safety for pedestrians; moreover, more definitive research is needed to establish engineering interventions appropriate to local circumstances and that meet the needs also contrasting of other vulnerable users as those with reduced mobility.

 ISSN 1913-9063 E-ISSN 1913-9071

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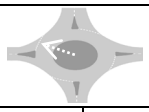
Table 1. Design elements for roundabouts*

		Roundabout category		
		Mini 14 m ≤ D_o < 25 m	Compact 25 m ≤ D_o < 40 m	Conventional D_o≥ 40 m
Circular roadway	one-lane entry [m]	7-8	7	6
	two-lane entry [m]	8.5-9	8.5-9	9
Entry approach	one-lane entry [m]	3.5	3.5	3.5
	two-lane entry 6 [m]	6	6	6
Exit [m]		4	4.5	4.5
Central island treatment		Fully traversable for 14 ≤ D_o < 18 Partially traversable for 18 ≤ D_o < 25	Raised curb	-

D_o: outer diameter of roundabout

**Norme funzionali e geometriche per la costruzione delle intersezioni stradali. Ministero Infrastrutture e Trasporti. [Geometric and functional standards for the construction of intersections. Infrastructure and Transport Ministry]. Decree April 19, 2006.*

Table 2. Roundabout design guidelines and manuals used in the world

Country	reference
France	*Conception des carrefours à sens giratoire implantés en milieu urbain*. Paris: Centre d'Etudes des Transports Urbains, 1988, 107 pp. *Carrefours Giratoires: Evolution des Caracteristiques Geometriques*, Ministere de l'Equipement, du Logement, de l'Amenagement du Territoire et des Transports, Documentation Technique 60, SETRA, 1988. Amenagement des Carrefours Interurbains, Chap. 4, Les Carrefours a Sens Giratoire, SETRA, CETE de l'Ouest (January 1996) pp. 56-87
Switzerland	*Guide Suisse des Giratoires*, VSS/OFR+FSR. Lausanne Fonds de Securite Routiere, Institut des Transports et de Planification, Ecole Polytechnique Federale de Lausanne, Switzerland, February, 1991 (Authors: Bovy *et al*).
UK	*Design Manual for Roads and Bridges* 6(2), Part 3, TD 16/93Geometric design of roundabouts. London: Department of Transport, 1993, 68 pp.
Australia	Guide to Traffic Engineering Practice-Part 6: Roundabouts. Austroads, Sydney, Au, 1993, pp. 66
US	*Synthesis of Highway Practice 264: Modern Roundabout Practice in the United States*. NCHRP, Transportation Research Board. Washington DC, 1998 (Author: Jacquemart G.) *Roundabouts an informal guide*". Us Department of Transportation, Federal Highway of Transportation, Publication n. FHWA-RD-00-067, 2000 (Authors: Robinson *et al*). *Roundabouts in the United States*. Washington DC: Transportation Research Board of the National Academies, NCHRP Report 572, 2007 (Authors: Rodegerdt *et al*). *Roundabouts: An Informational Guide* (2nd ed.). Washington DC: Transportation Research Board of the National Academies, NCHRP Report 672, 2010, (Authors: Rodegerdt *et al*). *Facilities Development Manual*, Wisconsin Department of Transportation, DM 11-2610, Chapter 11 *Design*, Section 26 *Roundabouts*, February 2011, http://roadwaystandards.dot.wi.gov
Germany	Kreisverkehrsplaetze-Leistungsfaehigkeit, Sicherheit und verkehrstechnische Gestaltung. (Roundabouts – Capacity, safety, and design), Strassenverkehrstechnik, vol. 6, 1991 (Authors: Brilon, W. and Stuwe, B)
The Netherlands	Eenheid in rotondes. Publicatie 126. CROW-Kenniscentrum voor verkeer, vervoer en infrastructuur, Ede, 1998

Table 3. Summary of safety studies at roundabouts (Granà, 2011)

Country	reference	method	results
Australia	Austroads, 1993	Before-and-after	Crash reduction after roundabout installed*: – 74 % in the casualty crash rate; – 32 % in property damage only; – 68 % in pedestrian casualty crashes per year. **control before roundabout: give way to the right – stop – give way.*
the Netherlands	Schoon and Van Minnen, 1994,	Before-and-after without control	crash reduction at single-lane roundabouts: – 73% in all pedestrian injury crashes – 89% for pedestrian fatality; – 63% for moped injuries; – 30% for cycle injuries.
France	Guichet, 1997,	Comparisons with rural intersections controlled traditionally	– less than 25% of serious injury crashes or fatalities at roundabouts; – 38 fatal or serious type injuries for every 100 crashes at roundabouts vs 55 injury or fatal crashes for every 100 crashes at controlled intersections; – crash frequencies 4 times higher at signalized intersections than roundabouts.
Sweden	Brude and Larson, 2000	Comparisons with signalized intersections	– vehicle-pedestrian crashes at the single-lane roundabouts were 3 to 4 times lower than predicted crashes at comparable signalized intersections; – for two-lane roundabouts, crash risk was similar to comparable intersections.
USA	Persaud B. et al., 2001	before-after study	– 39% overall reduction in crash rates; – 90% reduction in fatal crashes; – 76% reduction in injury crashes; – 30-40% reduction in pedestrian crashes; – 10% in bicycle crashes.
Crashes reported outside the United States	Elvik, R., 2003	meta-analysis of studies *(28 studies to obtain estimates of effect on road safety of conversions to roundabouts)*	– 30% to 50% reduction in injury crashes; – 50% to 70% reduction in fatal crashes; – the roundabout effect on injury crashes is greater in 4-leg intersections than in 3-leg intersections; – the roundabout effect is greater in intersections previously controlled by yield signs than in intersections previously controlled by traffic signals.

Table 4. Roundabout design elements affecting safety and operations (Rodegerdts et al., 2010)

element	safety	capacity
angle between entries	++	- -
circulatory roadway	-	+
entry	-	++
entry angle	- -	+
entry radius	-	+
flare lenght	ns	+
inscribed circle diameter	-	+

++ an increase in this measure represents a significant positive effect

- an increase in this measure decreases positive effects

- - an increase in this measure decreases significantly positive effects

ns the relationship was not specified

+ an increase in this measure represents a positive effect

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Table 5. Effects of roundabout design elements on safety (Rodegerdts et al., 2007)

Measure	crash category				
	single vehicle	entering - circulating	rear-end crashes on approach	pedestrian	Exiting - circulating
AADT	↑	↑	↑	↑	↑
Pedestrian volumes				↑	
Number of approaching lanes			↑	↑	
Number of circulating lanes		↑		↑	
Radius of vehicle path	↓				
entry deflection	↓	↓			↓
Percentage of motorcycles		↑			
Angle to next approach		↓			
Sight distance	↑				
Weaving length between splitter islands				ns	
Distance to first sight of roundabout				ns	
Length of vehicle path	↑				
85th percentile speeds	↑	↑	↑		↑
Reduction in 85th percentile speed	↑				
Posted speed limit				ns	

↑ an increase in this measure increases crash frequency

↓ an increase in this measure decreases crash frequency

ns the measure had a significant relationship with crash frequency but the relationship was not specified.

Table 6. Annual US Statistics on fatalities and pedestrian fatalities, 2000-2009

year	fatal crashes	fatalities	pedestrians fatalities	resident population	pedestrian fatalities per 1000,00 population	Pedestrian fatalities as a proportion of all fatalities [%]
2000	37526	41945	4763	282200	16.88	11.36
2001	37862	42196	4901	285100	17.19	11.61
2002	38491	43005	4851	287800	16.85	11.28
2003	38477	42884	4774	290300	16.44	11.13
2004	38444	42836	4675	293000	15.95	10.91
2005	39252	43510	4892	295800	16.54	11.24
2006	38648	42708	4795	298600	16.06	11.23
2007	37435	41259	4699	301600	15.58	11.39
2008	34172	37423	4414	304400	14.50	11.79
2009	30797	33808	4092	307000	13.33	12.10

Source: Query FARS data, available online: http://www-fars.nhtsa.dot.gov

Table 7. Annual fatalities and pedestrian fatalities in EU countries*, 2000-2009

year	fatalities (Eu-23)	pedestrian fatalities	pedestrian fatalities inside urban area	pedestrian fatalities as a proportion of all fatalities [%]	pedestrian fatalities inside urban area as a proportion of pedestrian fatalities [%]
2000	53647	10152	6793	18.92	66.9
2001	52305	9806	6602	18.75	67.3
2002	51223	9917	6687	19.36	67.4
2003	48351	8837	5950	18.28	67.3
2004	45288	7676	5904	16.95	76.9
2005	43399	7270	5599	16.75	77.0
2006	41204	8083	5450	19.62	67.4
2007	40684	8137	5517	20.00	67.8
2008	37265	7638	5361	20.50	70.2
2009	34061	6618	4689	19.43	70.9

Source: CARE (EU road accidents database), available online: http://ec.europa.eu/transport

Table 8. Annual US Statistics pedestrian fatalities by location, 2000-2009

location	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
intersection	1057	1017	1062	1012	957	994	1022	1075	1052	986
non intersection	3685	3848	3758	3734	3679	3865	3730	3584	3342	3061

Source: Query FARS data, available online: http://www-fars.nhtsa.dot.gov

ISSN 1913-9063 E-ISSN 1913-9071

Table 9. Design elements targeted at promoting pedestrian safety at roundabouts (Granà, 2011)

measure	description & comments	design rules and recommendations for accommodating pedestrians
Managing speed	Related to operational and design principles of roundabouts (priority to circulating vehicles, and deflection of entering vehicles that causes low entering speeds), include the geometric design of entry and exit approaches that at the same time aims to maximize visibility of the central island.	✓ entry curve radii are recommended to be 10-15 m (Guichet, 1997); ✓ at single-lane roundabouts: entry curb radii should be equal to 10-14 m (in urban areas) and 14-16 m (in rural environments); exit curb radii should be equal to 12-16 m (in urban areas) and 14-16m (in rural environments) (Brilon, 2011); ✓ at two-lane roundabouts and at larger roundabouts should be applied with no or few pedestrians; two-lane exits should be banned due to safety reasons (Brilon, 2011); ✓ transitions between entry lane curbs and the circle should follow circles with a small radius about equal to 12 -16 m at entry and 14-18 m at exit (Brilon, 2005); ✓ approach alignment is aimed to avoid high-speed tangential exit (Rodegerdts et al., 2010).
Separating pedestrians and vehicle by time	Roundabouts typically are not planned to include metering or signalization.	✓ pedestrian-actuated traffic signals can be placed at least 20 m from the yield line at entries (and exits) at high-volume sites in presence of disabled pedestrians and/or school children; the distance indicated is to prevent exiting vehicles queues extended up to the circulatory roadway (Robinson et al., 2000); ✓ the use of measures specifically designed to separate pedestrians and vehicles by time is often site dependent (Retting et al., 2003). *The "pedestrian hybrid signal" referred to as the HAWK crosswalk signal may be considered where a need to accommodate the visually impaired is demonstrated [Facilities Development Manual, Wisconsin Department of Transportation, DM 11-2610,Section 1.1., December 2011]*
Separating pedestrians and vehicle by space	Splitter islands on approaches are used to allow pedestrians to cross the road in two stages	✓ splitter islands are cut to allow pedestrians, wheelchairs, and bicycles to pass through (Robinson et al., 2000); ✓ splitter islands are recommended to be 1.6 to 2.5 m wide or 3.0 m (Doctors, 1995; Jacquemart, 1998); ✓ they are also aimed to separate traffic moving in opposing directions and to deflect and slow entering traffic.
Increasing pedestrian visibility	The required intersection sight distance is approximately half what is required for a signalized intersection because of reduced intersection speeds.	✓ no pedestrian activities are allowed on the central island; ✓ the crossing location is set back from the circulating roadway at a point behind one vehicle waiting at the yield point (at single-lane roundabouts) and one, two, or three car lengths at double-lane roundabouts; pedestrian crossings close to the circulatory roadway may reduce site capacity and further away may increase walking distances exposing pedestrians also to higher speeds (Jacquemart, 1998); ✓ provision of pedestrian high-visibility or zebra-striped crossings are recommended when pedestrian flows reach a certain minimum or depending on the vehicle/pedestrian conflict (Brilon, 1996, Sicherheit von Kreisverkehrsplatzen-unpublished paper; Doctors, 1995); ✓ when entries are flared pedestrian crossing before the flaring (*Design manual for roads and bridges*, London: HMSO, 1993).

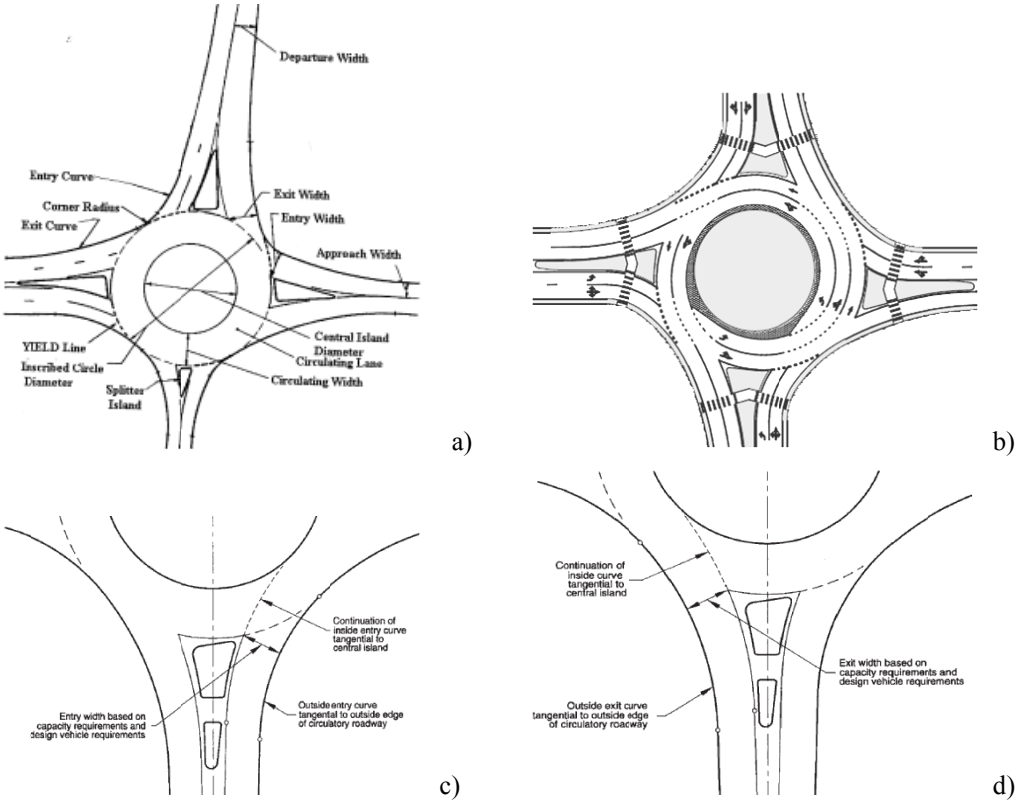


Figure 1. Geometric design elements for roundabouts from Taekratok (1998) and Rodegerdts et al. (2010)

LEGEND

a) basic geometric elements of a single-lane roundabout

b) two-lane roundabout with multilane major street and single lane on minor street

c) single-lane roundabout entry design

d) single-lane roundabout exit design

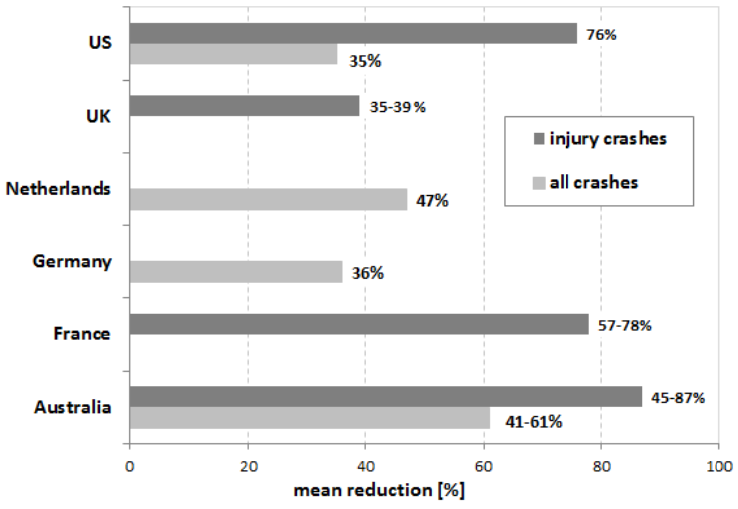


Figure 2. Mean reduction for all and injury crashes in various countries (Rodegerdts et al., 2010)

ISSN 1913-9063 E-ISSN 1913-9071

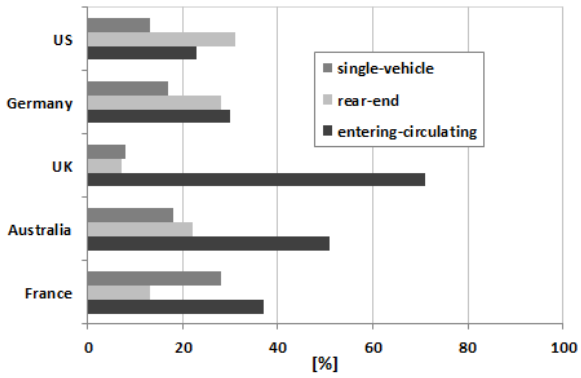
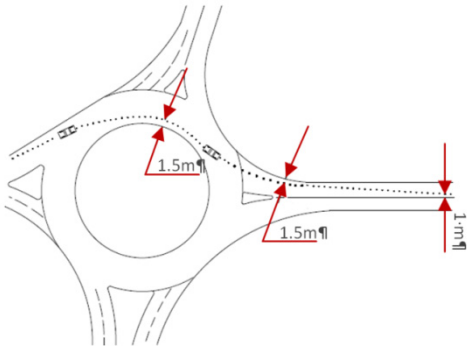


Figure 3. Percentages of major crash types at roundabouts reported in different countries (Brilon and Bondzio, 1998*; Rodegerdts et al., 2007)

*Note: data reported from France and UK are injury crashes; * Brilon, W. & Bondzio L. (1998). White Paper: Summary of International Statistics on Roundabout Safety (unpublished).*



design speed [km/h]	deflection curve [m]
19	18
24	30
32	55
40	88
48	131

Figure 4. Vehicle entry path curvature at a roundabout

Note: drawn from Roundabout design guide, Maryland, US, www.ite.org and Roundabouts: An Informational Guide, http://www.fhwa.dot.gov

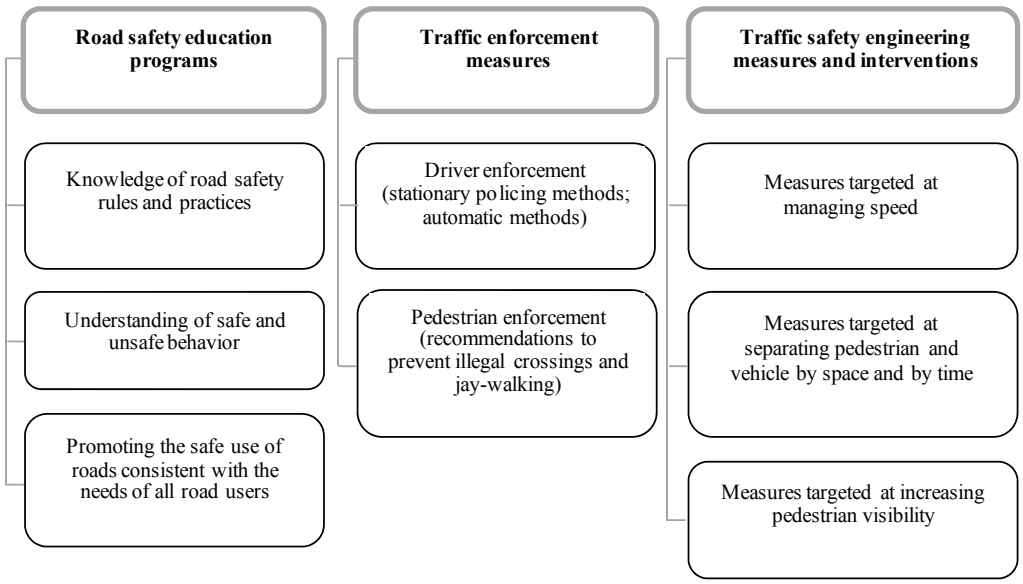


Figure 5. Measures targeted at improving pedestrian safety